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NASA CONTRIBUTIONS TO DEVELOPMENT OF SPECIAL-PURPOSE THERMOCOUPLES

A SURVEY

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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A SURVEY

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Foreword

The thermocouple has been used for measuring temperatures for more than a century, but new materials, probe designs, and techniques are continually being developed. Numerous contributions have been made by the National Aeronautics and Space Administration and its contractors in the aerospace program. These contributions have been collected by Midwest Research Institute and reported in this publication to enable American industrial engineers to study them and adapt them to their own problem areas. Potential applications are suggested to stimulate ideas on how these contributions can be used.

This publication is part of a series that brings NASA's contributions to the attention of industry.

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Contents

Introduction

In modern industry the thermocouple plays an important role in temperature instrumentation. The increasing need for temperature measurements in extreme environments has produced significant advancements in thermocouple technology; much of this technology has come from research in the aerospace and atomic energy areas. This survey reviews developments resulting from work performed by the National Aeronautics and Space Administration (NASA) and its contractors. The main thrust of the survey is to encourage nonaerospace applications of the results of aerospace research.

This survey is concerned with special-purpose thermocouples, their characteristics, and their application to difficult problems. The term "special-purpose thermocouple" means either: (1) a new combination of thermoelectric materials applied to the solution of either unique or conventional temperature-measuring problems or (2) the application of conventional thermoelectric materials in novel techniques of thermocouple fabrication, design, or instrumentation.* Most of the innovations which will be described are in thermocouple design and application techniques. Scientists, engineers, and technicians acquainted with these techniques, probe designs, and materials may use them to measure temperatures more satisfactorily in many industrial processes.

The historical development and the principles of thermocouple operation are reviewed in chapter 1. The chapter also includes a discussion of the selection of thermocouples, lists many of the thermocouples commonly used in industry, and calls attention to important symposia and seminars on temperature measurements.

In chapter 2, recent developments in thermoelectric materials for measuring cryogenic temperatures (below −190° F) are described. Guides and precautions for selecting and using thermocouples at low temperatures are given; potential applications also are indicated.

Chapter 3 discusses the thermoelectric materials and electrical insulators used in thermocouples for measuring temperatures above 3000° F. The characteristics and the limitations of metal thermocouples are reviewed, and NASA's activities in developing nonmetallic thermocouples are described. The development of a thermocouple to operate at 5400° F is cited and potential applications of such work are suggested.

Chapters 4, 5, and 6 discuss the application of special-purpose thermocouples to the measurement of gas temperatures, surface temperatures, and temperatures of solids. New thermocouples have been developed as a result of advances in such areas as rocket-nozzle design and testing, thermal protection systems, and experimental high-speed fluid dynamics. These chapters describe how thermocouples have solved temperature-measuring problems that were beyond the capabilities of conventional materials or techniques, e.g., the measurement of the rapidly changing temperature of hot gases and the continuous measurement of the surface temperature of an ablating solid. Procedures for selecting or designing these special probes are given in these chapters.

A variety of energy-measuring devices that use special thermocouples are described in chapter 7. These devices determine the quantity of heat transferred to a solid, such as a test model, an apparatus, or the wall of a test chamber. They derive this information from temperature measurements at specific locations in the solid or at specific time increments from the beginning of an experiment. Descriptions

*Literature regarding commonly used thermocouples and well established techniques is readily available.

of heat-flux gauges, a radiant-energy calorimeter, and an "intrinsic" thermocouple device are included in this chapter.

Developments associated with techniques of attaching thermocouples to test items to ensure maximum thermal contact are presented in chapter 8. Special methods of connecting metal-sheathed thermocouple wires to flexible lead wires are shown as well as other ways of using and handling metal-sheathed thermocouples.

Test circuits given in chapter 9 can be used to check out many thermocouples at remote locations. One of them permits measurement of the resistance of each wire or both wires of each thermocouple. Special reference junctions developed at NASA Centers also are described.

CHAPTER 1

Background

Thermocouple research programs have followed three lines: (1) developing new thermocouple materials, (2) developing techniques associated with the use of thermocouples, and (3) providing appropriate designs for various applications. The most commonly used thermoelements and thermocouple practices are now classified by the ASA Standards Institute following the practices recommended by the Instrument Society of America (ref. 1).

A great many metal and alloy combinations can be employed as thermocouples, and the list of techniques that can be used in their application is very long. Consequently, design and application of thermocouples is one of the most dynamic areas of instrumentation and measurement. New developments in thermoelectric thermometry continue to be a byproduct of many NASA research and development programs. Nearly all these developments have potential application in nonaerospace industries.

PRINCIPLES OF THERMOCOUPLE OPERATION

The use of thermocouples to measure temperature is based upon thermoelectric effects. Because adequate discussion of the physical phenomena involved in thermoelectricity is available in the literature (refs. 2–6), the treatment of these principles here will be quite brief.

Three thermoelectric effects are important in thermocouple technology: the Seebeck effect, the Peltier effect, and the Thomson effect. The first was discovered in 1821 by T. J. Seebeck, who found that an electric current will flow in a circuit consisting of two dissimilar metallic conductors if one junction where the two conductors are joined is at a higher temperature than the other. Discovery of the second effect is credited to Jean C. A. Peltier, who observed in 1834 that heat is liberated or absorbed when a current flows across the junction between two metals. The Thomson effect was first reported by Lord Kelvin (then Sir William Thomson) in 1847. He found that, when a current flows along a nonisothermal conductor, heat is liberated at any point at which the directions of the current and the heat flow are the same, and heat is absorbed at any point at which the current and heat flow are in opposite directions.

The current is so small in a thermocouple circuit that the temperature of the junction is not measurably influenced by the Peltier effect; the influence of the Thomson effect is even less. Thus, only the Seebeck effect makes the thermocouple practical.

The operation of a thermocouple as a temperature-measuring device is governed by three experimentally established laws:

(1) *The Law of the Homogeneous Circuit*—The application of heat alone cannot produce or maintain an electric current in a circuit consisting of a single homogeneous metal.

(2) *The Law of Intermediate Metals*—If a circuit consisting of any number of dissimilar metals is at a uniform temperature, the algebraic sum of the electromotive forces (emf) produced by thermoelectric effects is zero.

(3) *The Law of Intermediate Temperatures*—If a thermal emf, E_1, is generated in a circuit of two dissimilar homogeneous metals when the junctions are at temperatures T_1 and T_2, and a thermal emf, E_2, is generated when the junctions are at T_2 and T_3, then when the junctions are at T_1 and T_3 the thermal emf will be E_1+E_2.

These three laws can be combined to explain the operation of a thermocouple. In any circuit consisting of any number of dissimilar homogeneous metals, the algebraic sum of the thermoelectric emf's depends only upon the temperature of the junctions. It follows that the temperature difference between the junctions in a thermoelectric circuit of two dissimilar metals can be determined from a measurement of the thermoelectric emf. If the temperature of one of the junctions (the reference junction) is known, the emf provides a measure of the temperature of the other junction.

In the nearly 150 years since Seebeck's discovery, no satisfactory explanation of the mechanism by which thermal energy is converted into electrical energy in a thermoelectric circuit has been proposed. Nor is the functional dependence of emf on temperature fully understood; but, such inadequacies have not prevented the development of thermocouples as a practical means of temperature measurement.

COMMONLY USED THERMOCOUPLES

The most commonly used thermocouples are classified by ASA Standard C96.1–1964 (ref. 1) as Type *T* (Cu/Con*), Type *J* (Fe/Con), Type *E* (Ch/Con), Type *K* (Ch/Al**), Type *S* (Pt–10 Rh/Pt), and Type *R* (Pt–13 Rh/Pt). Calibration tables for these thermocouples are published in NBS Circular No. 561 (ref. 7). A summary of the properties of commonly used thermocouple materials and a bibliography of the related literature are presented in reference 8.

The selection of a pair of materials for use as a thermocouple depends upon numerous factors, e.g., temperature range of application, temperature-emf relationship, material melting points, effects of the environment on mechanical, chemical, and thermoelectric properties, ease and reproducibility of manufacture, and material cost. This list is not complete, and the extent to which each of these factors enters into the selection of thermocouple materials depends upon the specific application.

*The first thermoelement in a combination has a positive signal with respect to the second when the temperature of their junction is above their reference junction.

**Chromel and Alumel are registered trademarks of the Hoskins Manufacturing Company, Detroit, Mich.

IMPORTANT SYMPOSIA AND SEMINARS

Several symposia and seminars, specifically dealing with temperature measurement, have discussed the principles of thermometry and current developments. Proceedings of the first such symposium, in 1919, were published only in individual papers. Proceedings of the next symposium, in 1939, were published in 1941 as volume I: "Temperature—Its Measurement and Control in Science and Industry." Another symposium occurred in 1954 and its proceedings appeared as volume II in 1955. The symposium in 1961 was the largest, and its proceedings, volume III, cover basic concepts, standards and methods; applied methods and instruments; biology and medicine. These volumes were all published by the Reinhold Publishing Corporation.

Seminars specifically dealing with high-temperature thermocouples for use in nuclear energy environments were held in 1959 and 1965. The proceedings, "High-Temperature Thermometry," TID–7586 (1959) and WASH–1067 (1965), were published by the Atomic Energy Commission. The proceedings of the 1965 seminar are available at nominal cost from the Clearinghouse for Federal Scientific and Technical Information, U.S. Department of Commerce, Springfield, Va.

CHAPTER 2

Thermocouples for Cryogenic Temperatures

The term "cryogenics" appeared in the 1870's but did not become popular until after 1950. The term is derived from the Greek words *kryos*, meaning "frost," and *genes*, implying "generating." In practice, cryogenics has implied the production and use of low temperatures and low-temperature techniques. Such temperatures have become important in many areas of science and engineering, medicine and surgery, electronics, instrumentation, food technology, fuel supplies, and space technology.

Temperature measurement has been a critical factor in all cryogenic research and development. For convenience, most cryogenic temperatures are expressed on the absolute temperature scale named in honor of Lord Kelvin, i.e., degrees Kelvin (°K). In this survey we will continue this practice for the cryogenic temperatures, but important temperature points will also be expressed as degrees Fahrenheit or °F. The Kelvin scale has the same interval as the Celsius temperature scale (°C); however, zero degrees on the Kelvin scale is at absolute zero or −273.16° C (−459.7° F). On the Kelvin scale, liquid helium (LHe) under normal conditions boils at 4.2° K (−452.1° F). Cryogenic temperatures are generally considered those temperatures below 150° K (−190° F).

Cryogenics first contributed to aerospace technology in 1926 when Professor Goddard demonstrated the feasibility of rocket launching with an engine using liquid oxygen (LOX). The liquid hydrogen/oxygen (LH_2/LOX) system is now used because it provides high energy and the liquids are available in large quantities. The national effort to develop operational cryogenic systems for rocket launches has contributed to liquefaction plant developments and to applied research and development. Consequently, considerable emphasis has been placed on cryogenic temperature-measurement devices.

THERMOCOUPLE COMBINATIONS FOR CRYOGENIC APPLICATIONS

Thermocouple combinations for cryogenic applications have been the subject of extensive investigations for several decades, and developments have been reported in the annual volumes of "Advances in Cryogenic Engineering" (Plenum Press).

Several commercial thermocouple combinations are now used for measuring cryogenic temperatures. The calibration data for the following thermocouple systems are available from the National Bureau of Standards (NBS) at Boulder, Colo.:

(1) Cu/Con
(2) Cu/Au–2.1Co
(3) Cu/Ag–0.37Au
(4) Ch/Al
(5) Ch/Con
(6) Ch/Au–2.1Co
(7) Ag–0.37Au/Con
(8) Ag–0.37Au/Au–2.1Co.

NASA PROGRAMS FOR CRYOGENIC THERMOCOUPLES*

At Marshall Space Flight Center (MSFC), work is being supported on direct applications of cryogenic thermocouples. In one program (ref. 9) a comparison has been made of 30-, 36-, and 40-gauge Cu/Con thermocouples and 30-gauge thermopiles as sensors for supercooling in liquid-level probing. The results show that

*No attempt is made here to include the numerous NASA-supported programs in which the thermocouple efforts played only a minor role.

sensors are supercooled and indicate a temperature actually lower than that of the liquid when they are removed from a cryogenic fluid. The response times of the thermocouples and thermopiles depend upon the size of the wire, its coating, and the mounting arrangement of the sensor. The effect of supercooling must be considered whenever thermocouple (and other) sensors are used to detect cryogenic liquid levels.

In a different program, an exhaustive evaluation and calibration has been made of Cu/Con and Cu/Au2.1Co thermocouples for use as LH_2 level detectors (ref. 10). Both short- and long-term (2½ years) stability studies of these thermocouples were made. Although the Cu/Au–Co thermocouples showed a higher sensitivity than the Cu/Con thermocouples, neither system proved satisfactory for liquid level measurements. The Cu/Au–Co thermocouples (1) should be calibrated at 3- to 6-month intervals to correct for thermocouple drifts, (2) should not be exposed to temperatures above ambient, and (3) should be handled as little as possible at room temperature to avoid effects of cold-working.

In another MSFC program, at Aerojet-General Corporation (ref. 11), an unusual combination of sensors has been developed into a single probe to measure the temperature of liquid and gaseous hydrogen from −423° to +140° F. The design combines in one probe a Ch/Con thermocouple with a carbon resistor. As shown in figure 1, both a constant current power supply and the thermocouple junctions are connected across the carbon resistor. The probe utilizes the high sensitivity of the carbon resistor at cryogenic temperatures (fig. 1, curve a) and the moderate sensitivity of the thermocouple at higher temperatures (fig. 1,

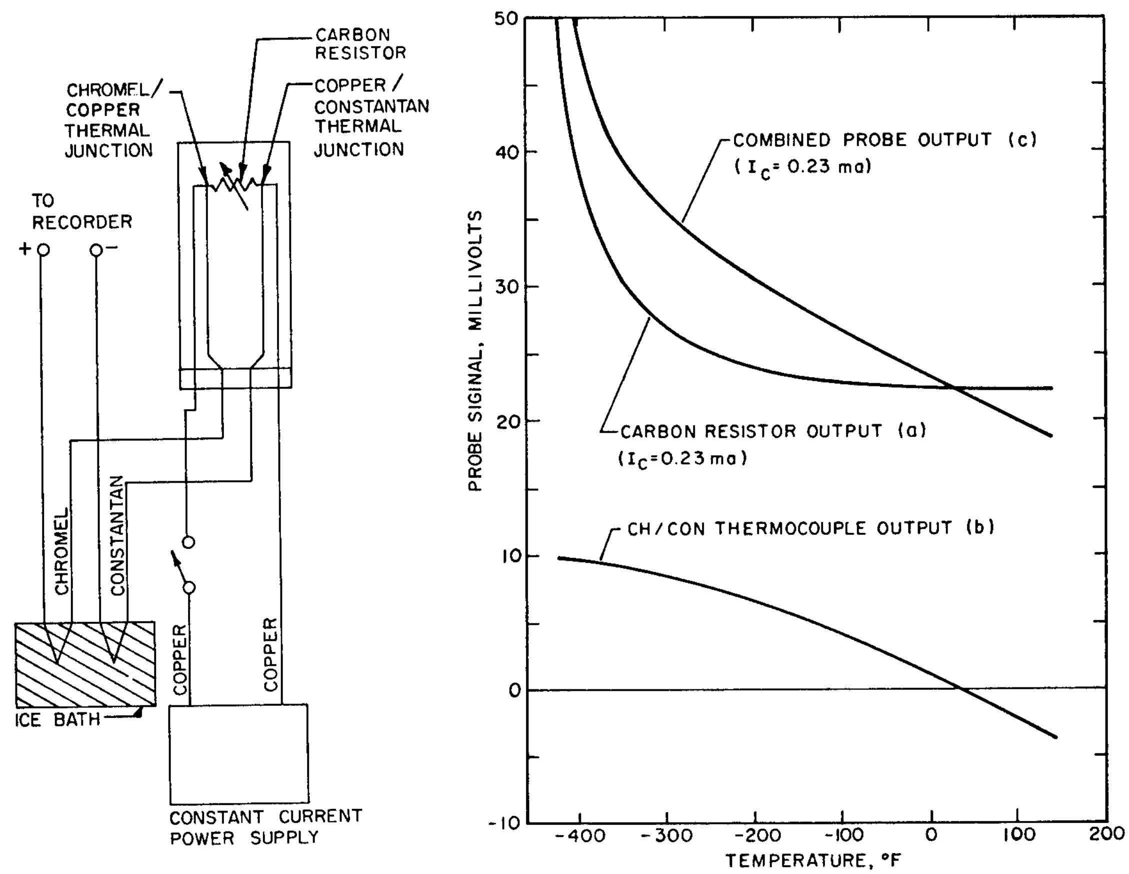

FIGURE 1.—Operational circuit and calibration curves for wide-range temperature probes for measurements from −423° to +140° F.

curve b). Thus, the resultant probe sensitivity (fig. 1, curve c) is high throughout its operating range and more linear in its response than the carbon resistor alone. A partially assembled and a completed probe are shown in figure 2.

The measurement of ullage gas temperatures (ref. 12) in liquid hydrogen rocket tanks (temperatures of the gases directly above the liquid) requires a fast-response temperature sensor that is operable in the cryogenic temperature range. Computer studies and model tests at MSFC have led to the development of a "slingshot" thermocouple (fig. 3), so-called because it has a Y-shaped frame to support it and its connecting wires. Preliminary designs were based on a polytetrafluoroethylene-insulated slingshot thermocouple that MSFC has used satisfactorily in liquid oxygen.

Specifications for the slingshot thermocouple consisted of a time constant of 2 seconds or less at cryogenic temperatures in hydrogen gas at two atmospheres pressure. These specifications required a temperature sensor well-insulated from its support and one that would have a low heat capacity. Most time-response data for thermocouples are derived from their use in high-velocity gas streams or in fluids with high heat capacities. Therefore, an experimental evaluation of the proposed thermocouple was necessary; no commercial thermocouples or other types of temperature sensors with the required strength had an adequate time constant.

Thermocouple probes were fabricated and tested by Beech Aircraft Corporation under contract to MSFC (ref. 12). The minimum thermocouple wire size sufficient to withstand gas velocities to 30 fps was 10 mils; therefore, the sensing elements were fabricated from this size wire. The controlling parameter in the design was the time constant, defined as the time required for the junction to respond to 63.2 percent of a step change in the temperature of the surrounding gas. The effects of several parameters on response time were investigated. These included:

(1) Thickness of the polytetrafluoroethylene Y-shaped frame

(2) Frame made of 18-gauge Cu/Con thermocouple wire

(3) Dimensions of the frame

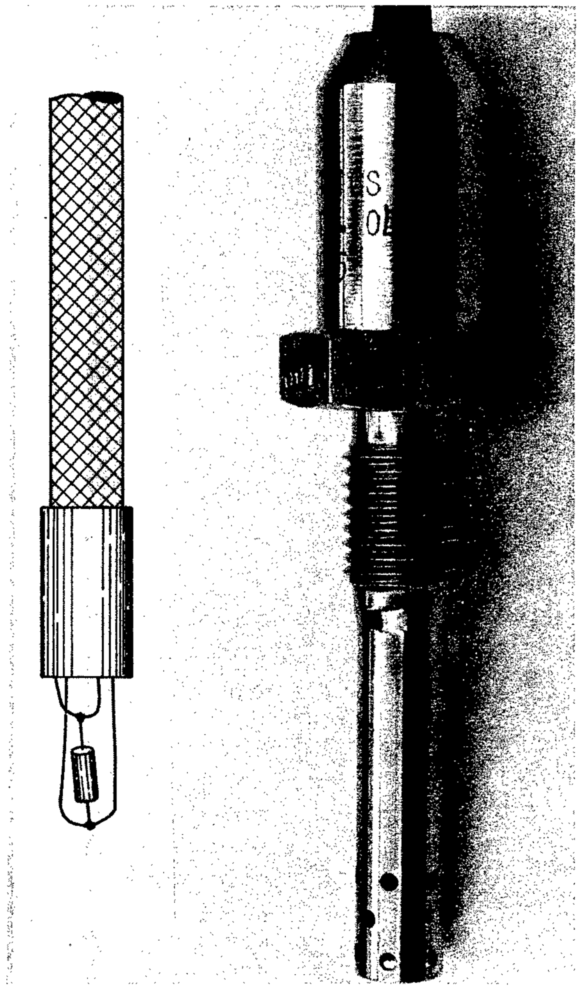

FIGURE 2.—Insert assembly and completed assembly of wide-range temperature probe developed for MSFC.

(4) Angle formed by the thermocouple junction

(5) Orientation of the thermocouple with respect to the horizontal

(6) Thermocouple junction weld

(7) Welds on lead wires in relation to the frame

(8) Cleaning the thermocouple wire at the junction

(9) Effect of varnish and insulation

(10) Speed of removal of the probe from the liquid.

The step change in environment temperature was obtained by moving the sensor from saturated liquid into the warmer gas above

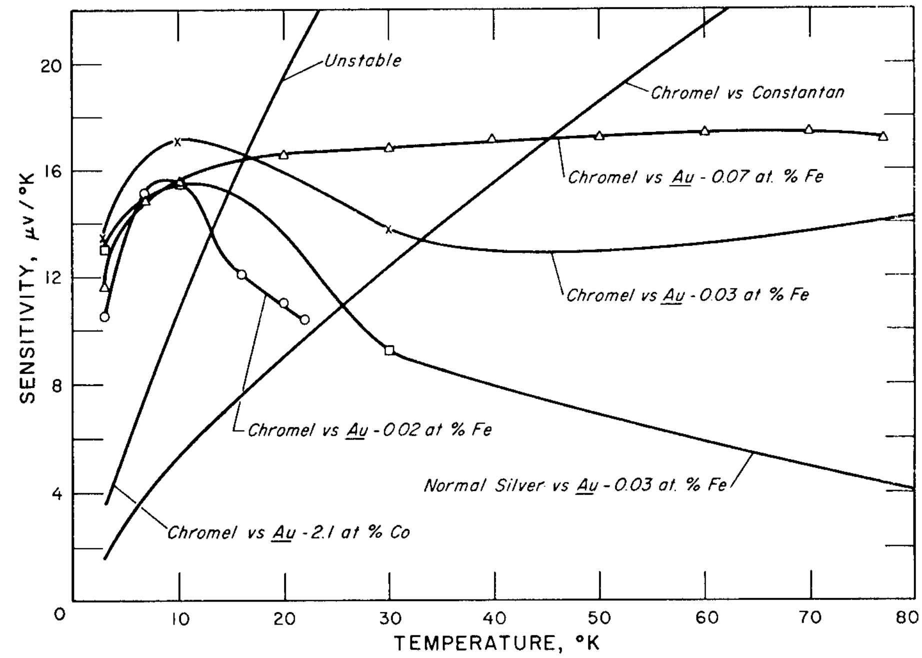

FIGURE 3.—Slingshot thermocouple for measuring the temperatures of the gases directly above liquid hydrogen in rocket fuel tanks.

the liquid level. All thermocouples were Cu/Con and were tested in hydrogen and nitrogen. They were also tested in flowing liquid and gases; some of them successfully withstood liquid velocities of 32 fps and gas velocities of 50 fps.

The results of tests of 45 probes indicated that durable, fast-response thermocouples can be fabricated in quantity and have reproducible response times. The recommended probe design includes: (1) uninsulated wire with a wire diameter as small as possible consistent with requirements of mechanical strength; (2) a lightweight wire frame with a support distance of at least 3 in. (A 1-in. frame had a time constant of 5.0 sec, 2-in. a constant of 2.0 sec, and 3-in. a constant of 1.1 sec); (3) the plane of the wire supports about 30 degrees above horizontal. (The time constant for the angle of 30 degrees above horizontal was 0.63 sec, 0 degree was 1.1 sec, and 30 degrees below horizontal was 1.5 sec); (4) an included angle of about 75 degrees between the leads at the thermal junction. (For an included angle of 100 degrees, the time constant was 50 percent greater; and for 145 degrees, the time constant was doubled); and (5) a spot-welded thermocouple junction with all excess wire carefully trimmed. (Trimming excess wire resulted, in some cases, in a decrease of the time constant from 3.8 to 0.5 sec.)

To ensure reliable cryogenic temperature measurements in space programs, NASA has supported exhaustive testing at NBS (Boulder) of commercially available low-temperature thermocouples (ref. 13). Ultimately this work will (1) establish standard calibration tables for each thermocouple material relative to a common reference metal, (2) establish standard calibration tables for each pair of thermocouple materials, (3) determine for each alloy the effects of inhomogeneity and interchangeability, and (4) determine for each alloy its sensitivity to physical abuse, such as straining or kinking. An interim phase of this program will provide smoothed calibration tables from available thermocouple calibration data and investigate several Au–Fe alloys for more accurate thermoelectric temperature measurements in the LH_2 to LHe temperature range, i.e., 20 to 4.2° K.

The increasing use of cryogenic fluids has shown the need for more reliable information concerning thermocouple materials. In reviewing thermocouple technology, it becomes evident that the present alloys are not optimum materials. Ideally the alloys calibrated for thermocouples should be those selected from the plateaus of curves showing thermoelectric power as functions of composition. Such alloys would show the least variation between different lots of material from the same or various commercial sources. No specific project to determine optimum alloys is under way; nevertheless, the present NASA–NBS effort, when completed, will be a significant contribution to cryogenic thermocouple technology. The initial results from this work are already providing important guides in selecting and using thermocouples for low-temperature measurements.

Table 1 shows the results of determining the effect of inhomogeneity and interchangeability of commercial cryogenic thermocouple materials from the NASA–NBS work. These data now provide definite guidelines for manufacturers during their wire production and for the user when selecting, checking, and using thermocouples. The Au–Fe and Fe wires showed large effects from inhomogeneities which cause large deviations from standard calibration tables. Chromel, Alumel, and constantan generally showed about the same inhomogeneity effects between ice and LN_2 temperatures as between ice and LHe temperatures.

TABLE 1.—*Thermocouple Wire Inhomogeneity Data* [a] *(ref. 13)*

Material	Company	Short length [b]			Medium length [c]		Different spools [d]	
		Equilibrium		Dynamic	Equilibrium		Equilibrium	
		Liq N_2	Liq He	Liq N_2	Liq N_2	Liq He	Liq N_2	Liq He
Chromel	A	0. 5μv	0. 9μv	5. 5μv	2. 2μv	2. 2μv	28. 0μv	33. 4μv
	B	1. 0	1. 2	6. 9	1. 0	1. 0	38. 0	39. 1
	C	2. 6	2. 6	8. 2	4. 5	4. 5	4. 4	6. 1
Iron	D	7. 5	8. 1	10. 1	20. 0	20. 0	55. 0	57. 3
	E	2. 2	2. 2	8. 1	1. 6	1. 6	15. 0	15. 0
Copper	F	0. 4	0. 4	1. 0	0. 4	0. 7	0. 5	0. 5
	G	0. 2	1. 4	1. 1	1. 9	7. 6	4. 1	37. 9
Alumel	H	0. 7	0. 7	13. 7	3. 8	4. 9	42. 0	45. 4
	I	1. 9	2. 4	14. 1	2. 2	2. 2	1. 7	2. 8
	J	2. 0	2. 0	21. 4	2. 6	2. 6	4. 6	4. 6
Constantan	K	0. 9	1. 2	1. 3	1. 6	1. 7	6. 6	6. 6
	L	3. 0	3. 0	5. 1	2. 4	2. 5	26. 0	27. 7
	M	2. 8	2. 8	8. 3	10. 8	12. 5	36. 0	44. 4
	N	1. 6	2. 1	6. 8	5. 8	5. 8		
Ag 0.37 Au	O	0. 5	0. 6	2. 0				
	P	0. 2	0. 2	2. 7				
Au 0.03 Fe	Q	2. 4	14. 7	16. 3				
Au 0.07 Fe	R	6. 3	16. 0	18. 0				

[a] Reported data are maximums.
[b] Continuous length of wire—approximately 15 ft.
[c] Compares front and back ends of a single roll—100 to 500 ft.
[d] Widely separated lengths of wires from different spools.

The effects of kinking or straining thermocouple wires are shown in table 2. In the "kink" tests, one leg of the thermocouple was deliberately kinked six places in the region of the sharpest temperature gradient. In the "strain" tests, one leg of the thermocouple was elongated by 2 percent. Table 2 shows that errors in thermocouple signals may occur when thermocouples are roughly handled or accidently abused.

Differential thermocouples of various materials were spot checked between ice and LN_2 temperatures and between LN_2 and LHe temperatures. The results of these tests, presented in table 3, show significant departures from earlier data published in NBS Circular 561 but good agreement with the interim data distributed in 1965 (ref. 13). Thus, the interim data appear to be adequate for most engineering applications.

Although thermocouples now appear satisfactory for temperature measurements down to the LH_2 range, measurements below the LH_2 range still present problems. While the Ch/Au–2.1Co thermocouples provide high sensitivity in this region, they show instabilities because Au–2.1Co is a supersaturated solid solution rather than an alloy at room temperature. Several "exotic" materials have been evaluated as alternate materials. These include a variety of Au and Fe alloys. The Au–Fe alloys are the most promising of the new materials tested because of their sensitivity characteristics. Figure 4 shows typical thermocouple sensitivity for the Au–Fe alloys when paired with either Ch or Ag–0.31Au wire as the positive thermoelement. These curves illustrate the high sensitivity of the Au–Fe alloys as compared to the Au–2.1Co alloy in the 1° to 15° K range. The Ch/Au–0.07Fe appears to be sufficiently sensitive for use over the entire cryogenic range.

TABLE 2.—*Kink or Strain Effect on Thermocouple Wire (ref. 13)*

Material	Company	Kink [a]			Strain [b]			Undamaged [c]		
		Equilibrium		Dynamic	Equilibrium		Dynamic	Equilibrium		Dynamic
		Liq He	Liq N_2	Liq N_2	Liq He	Liq N_2	Liq N_2	Liq He	Liq N_2	Liq N_2
Chromel	A	6. 0μv	6. 0μv	10. 5μv	8. 5μv	7. 2μv	9. 0μv	0. 4μv	0. 4μv	4. 2μv
	B	1. 6	1. 6	5. 8	5. 7	4. 4	4. 3	1. 2	1. 0	6. 9
	C	2. 2	2. 2	17. 1				0. 1	0. 1	5. 5
Alumel	D	1. 2	0. 8	7. 4	4. 0	2. 8	7. 3	1. 0	1. 0	7. 6
	E	1. 0	1. 0	6. 6	1. 3	1. 3	9. 8	0. 7	0. 7	10. 0
	F	3. 3	3. 3	9. 7				1. 4	1. 4	12. 3
Constantan	G	1. 3	1. 3	5. 4	4. 7	4. 7	6. 9	3. 0	3. 0	4. 0
	H	1. 4	1. 4	5. 9				0. 4	0. 3	0. 8
	I	4. 8	3. 8	8. 0				2. 1	2. 1	6. 8
Ag 0.37 Au	J	0. 6	0. 6	2. 7	1. 1	1. 1	2. 2	0. 2	0. 2	1. 1
Au 0.03 Fe	K	1. 4	1. 4	16. 3				14. 7	2. 4	11. 6
Au 0.07 Fe	L	20. 6	6. 2	18. 0				16. 0	6. 3	13. 0

[a] Kinks were formed by forming a loop in the wire and applying tension; 6 kinks were made on each wire.
[b] The wires were strained by a 2-percent elongation.
[c] The "undamaged" results given here are for one particular sample from each company, while the corresponding "short length" tests in table 1 represent the maximum values from several spools from each company.

TABLE 3.—*Differential Thermocouple Test Data Compared to NBS Table 561 and Interim Values (ref. 13)*

Material	Percentage Deviations [a]		
	Ice temperature to Liq N_2		Liq N_2 to Liq He
	Interim tables [c] (%)	NBS Cir. 561 [b] (%)	Interim tables [c] (%)
Cu vs Au/Co	+0.01 to +3.93		−0.13 to +3.80
Cu vs Constantan	−0.11 to +0.31	+0.89 to +1.31	−2.07 to −1.70
Fe vs Constantan	−1.41 to +12.88		−2.49 to −1.67
Chromel vs Alumel	−0.45 to +0.23	+2.14 to +2.27	−0.54 to +2.3
Chromel vs Au/Co	+1.13 to +3.75		+0.47 to +4.35
Chromel vs Constantan	−0.19 to +0.72	+0.38 to +1.29	−1.68 to +1.07

[a] In comparing the experimental data to existing data, a positive percentage indicates the experimental data were higher than the existing data. The values used here are the maximums found in testing several thermocouples of each type.

[b] National Bureau of Standards Circular 561, "Reference Tables for Thermocouples." The emf's corresponding to Liq N_2 temperature had to be extrapolated. No values are available for the He to N_2 range.

[c] Interim values are from low temperature thermocouple tables by Powell et al., Cryogenics Division, National Bureau of Standards, Boulder, Colo., distributed Summer 1965, as reported in NBS Report 8750.

GUIDES FOR SELECTING AND USING THERMOCOUPLES AT CRYOGENIC TEMPERATURES

The measurement of temperatures in the cryogenic region above 50° K with thermocouples can be made with normal precautions. However, considerable care must be taken in selecting and preparing thermocouples for temperatures below 50° K, and sophisticated instrumentation must be used if accurate measurements are desired. In general, the final thermocouple selection requires a compromise in the selection of instrumentation, environment, and thermocouple.

Thermocouple instrumentation involves factors beyond the scope of this survey. Obviously the instrumentation must provide adequate range to monitor thermocouples over the desired temperature span, stability and sensitivity to provide the desired accuracy, suitable display of the data, and auxiliary features to control automatically the temperature from the thermocouple or instrument signals, if required.

The environment expected for the measurements is an important factor in selecting the thermocouple. Thermocouple wires are available either bare or with a variety of insulations. For accurate temperature measurement and long life, the thermocouple material should be isolated from chemical reaction with its environment. Although such undesirable reactions occur more frequently in high-temperature measurements, they can occur at low temperatures when thermocouples are used in corrosive liquids, vapors, or gases.

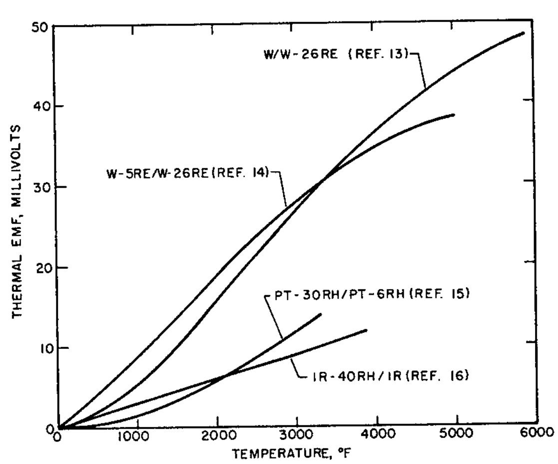

FIGURE 4.—Sensitivity of gold-iron alloys when paired with Chromel or normal silver.

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Similarly, insulation for thermocouple wires must be compatible with the environment and must prevent electrical shorting. All standard commercial insulations (including the recent ceramic coatings designed for the high-temperature ranges) are serviceable at cryogenic temperatures. However, special care must be taken to avoid electrical conduction through the reference ice bath; for this purpose, polytetrafluoroethylene and thermoplastic coatings have proved superior to enameled coatings.

Special care must also be taken with thermocouples in corrosive or oxidizing cryogenic gases or fluids. Organic insulations are hazards and should be avoided under such conditions. Also, special consideration must be given to thermocouples in an evacuated system at cryogenic temperatures. The baked enamel-type coatings are satisfactory for use in vacuum because their outgassing rate is extremely low.

The critical and limiting factors in cryogenic temperature measurements with thermocouples are primarily determined by the sensors themselves. For most engineering applications, commercial thermocouple materials are suitably calibrated from about 20° K to room temperature and above (ref. 13). Even so, each application should involve a careful consideration of the thermocouple materials, the temperature range of the application, and the dependability of its calibration. In critical applications, self-checking and auxiliary calibration techniques should be employed to ensure reliable readings.

Several factors significantly affect the accuracy and performance of cryogenic thermocouples. These, in part, differ distinctly from factors affecting the use of thermocouples at higher temperatures. For this reason, these factors are discussed below as general guides to selecting and using cryogenic thermocouples.

(1) At low temperatures the thermocouple sensitivity (the so-called thermoelectric power, dE/dT) falls to only a fraction of its room-temperature value. Thus, more sensitive instruments are required to detect small changes in temperatures. Greater care also must be taken to ensure that no changes occur in the reference junction temperature.

(2) Inhomogeneities in thermocouple wires act as signal sources if thermal gradients exist along the wire. Thus, care must be taken to select high quality wire and to keep it free from strains during its fabrication, installation, and use. Thermocouple configurations that reduce thermal gradients at critical positions along the thermocouple wires are preferred.

(3) The temperature of the thermal junction may be affected by heat transfer along the thermocouple wires. This factor can be reduced by selecting thermocouple wires with low thermal conductivity, making them small in cross-sectional area, and designing a system having adequate thermal conditioning of the wires to prevent heat conduction through them to the thermal junction.

(4) The effective thermal junction may not exist at the apparent physical junction because of electrical shorts or leakage through insulation.

(5) Temperature gradients across the thermocouple junction can produce error potentials. Junctions involving mechanical joints, solders, and even welded beads introduce intermediate materials that can produce error potentials. These errors can be kept negligible if the temperature gradient across the junction is kept very low.

(6) The processes of fabricating thermocouple wires generally create inhomogeneities which vary both randomly in short sections of wire and continuously across any given spool of wire. Thus, a fixed calibration table for a thermocouple system does not exist for any class of wires or for any spool of the same wire. When reporting temperature data, one must either accept the general standards of accuracy or provide a consistent means of calibrating each thermocouple.

One or more of these factors can markedly influence the accuracy of thermocouple measurements. The most important factors limiting reliability in temperature measurements with thermocouples are the inhomogeneities in materials and the noninterchangeability of materials. With any selected thermocouple system, the remaining factors of heat conduction, thermal gradients, current leakage, and cold-working limit the temperature-measurement accuracies.

POTENTIAL INDUSTRIAL APPLICATIONS

Some of the areas where NASA-developed thermocouples or techniques might prove beneficial are suggested below.

Instrumentation Industry

Under NASA sponsorship, NBS (Boulder) has studied various thermocouples for sensitivity and other characteristics from near absolute zero to room temperature. Ch/Con thermocouples are recommended instead of Cu/Con for instrumentation systems because of their higher sensitivity and lower heat-conduction errors. Furthermore, the NASA–NBS work on inhomogeneity and kink or strain effects in thermocouple circuits indicates the need for instrumentation engineers to be aware of these effects to reduce errors in their temperature instrumentation systems.

The combination of a resistor and a thermocouple into a single probe provides a more linear response to temperature changes from −200° to 100° F than the individual sensors. Since linearity is an important factor in temperature control, this probe could be used in instrumentation systems for closer quality control in any production cycle operating over this range.

Electronics Industry

When electronic devices are operated at cryogenic temperatures to improve their signal-to-noise ratio, it may be more practical in some situations to cool them by a cold gas than by liquefied gas. Hence, a rapid-responding sensor, such as the slingshot thermocouple described in this chapter, would be appropriate. Furthermore, the use of Ch/Con thermocouples instead of Cu/Con would reduce the heat leak by conduction into the cryogenic environment and provide greater sensitivity. All these factors should provide a more closely controlled temperature environment for electronic devices.

Natural Gas Storage Industry

The storage of natural gas as a liquid at −260° F is an efficient way to meet peak demands for natural gas. When the gas is distributed for domestic and industrial use, it must be warmed in a heat exchanger to ambient temperatures before distribution. The slingshot thermocouple could be used for measuring the exit temperature of the gas from the heat exchanger to provide a more rapid temperature response with improved control and greater efficiency in the heat exchanger operation.

Steel Industry

Huge quantities of LOX are used in furnaces for steel production. The temperature instrumentation for the LOX systems could operate with improved reaction times if the slingshot thermocouple design were used at positions of precise temperature control of the gas phase. This fast-responding thermocouple was developed by MSFC particularly for LOX or gaseous oxygen systems and could be a direct technology transfer.

In the steel industry, as in other industries, Ch/Con thermocouples could also provide more accurate control temperatures in LOX production and consumption cycles when substituted for the less sensitive Cu/Con thermocouple.

Food Processing Industry

Freezing of foods by liquid nitrogen and cold gaseous nitrogen has become a thriving industry in the last few years. More efficient use of the cold gas could possibly be achieved if the fast-responding slingshot thermocouple design and the high-sensitivity Ch/Con thermocouple were used.

CHAPTER 3

Thermocouples for Use Above 3000° F

The development of high-temperature thermocouple materials and techniques has received impetus from the temperature-measurement requirements of programs related to gas turbines, rocket engines, reentry heat shields, and other facets of NASA's work. Advances also have been made as a result of nuclear rocket studies on Project Rover by the Atomic Energy Commission (AEC) and the NASA Space Nuclear Propulsion Office.

This chapter will describe thermocouple developments where the high operating temperature was the primary factor in selecting the materials and design for stable and accurate measurements. The operating temperature not only influences the selection of materials for the thermoelement but also for the insulation and sheathing. Insulations must withstand extreme temperatures and be compatible to thermoelement materials at elevated temperatures. Sheathing or protection tubes must retain sufficient mechanical strength at the operating temperature to enable the thermocouple to be a serviceable instrument.

Thermoelement combinations used for temperature measurements above 3000° F generally fall into one of three categories:

(1) Noble-metal thermocouples
(2) Refractory-metal thermocouples
(3) Nonmetallic thermocouples.

The thermal emf's of some of the commonly used, high-temperature metallic thermocouples at NASA centers are shown in figure 5.

In addition to discussing thermoelement combinations, this chapter will describe the electrical insulation materials that are used or are being studied for use as thermocouple insulators at temperatures above 3000° F. The shunting effect encountered because of the loss of resistance at the high temperatures generates temperature-measurement errors Hence this effect is described in detail. A guide for selecting thermocouple materials summarizes the many factors that must be considered in using thermocouples at high temperatures.

NOBLE-METAL THERMOCOUPLES: IRIDIUM-RHODIUM THERMOELEMENTS

Interest in the use of iridium as an element in high-temperature thermocouples is a natural consequence of its high melting point (4429° F), moderate resistance to oxidation at high temperatures, and strength at high temperatures. Use of Pt–Rh alloys for thermocouples above 3000° F is marginal because this temperature is near their melting points; instead, thermocouples with Ir–Rh and Ir thermoelements are now widely used at NASA centers for air-breathing engine research. Although considerable information is available concerning the properties of iridium, property data for the iridium-rhodium alloys are scarce. The upper temperature limit for Ir–Rh/Ir thermocouples corresponds to about 3900° F.

Major research efforts at various laboratories have been devoted to studying the calibration and the stability of the Ir–60Rh/Ir and Ir–40 Rh/Ir thermocouples. Investigators have previously studied the Ir–60Rh/Ir thermocouple; but, because the aerospace program demanded improved performance, other alloys were evaluated for the positive thermoelement of the thermocouple. The Ir–40Rh/Ir thermocouple is being adopted by NASA centers for oxidizing atmospheres. Because of the demand for calibration data, the National Bureau of Standards has published reference tables for Ir–Rh/Ir thermocouples using alloys ranging from 10- to 90-percent rhodium as the positive thermo-

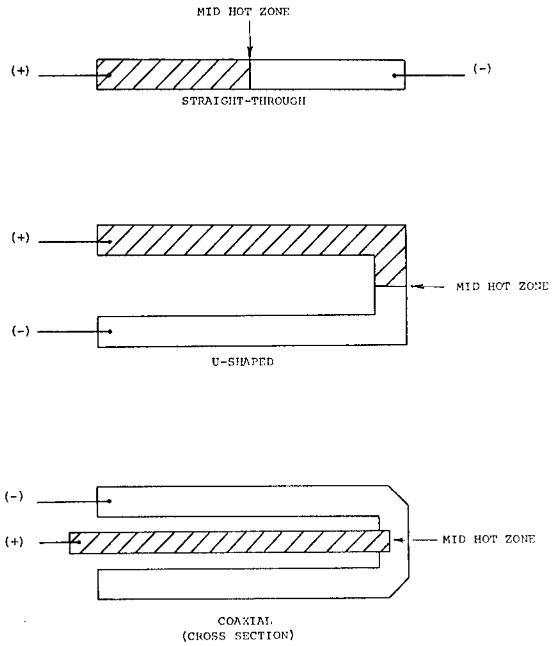


FIGURE 5.—Thermal emf of some commonly used high-temperature metallic thermocouples used at NASA centers.

element (refs. 17 and 18). The maximum output at a given temperature occurs near the 50-percent alloy; however, the thermal emf is practically insensitive to rhodium content over the range of 40- to 60-percent rhodium. The calibration studies at NBS conclude that Ir-Rh/Ir thermocouples with an alloy containing nominally 40-, 50-, or 60-percent rhodium can be used for temperature measurements up to 3900° F; their accuracy will normally be within ±40° F if the calibration tables are used. Improved accuracy can be obtained by calibrating each thermocouple.

Scientists at NASA centers and elsewhere have found that iridium selectively oxidizes out of the Ir–Rh alloy when the alloy is operated at high temperatures. Hence, an alloy of Ir–40Rh gradually shifts to the alloy of Ir–50Rh and on to Ir–60Rh alloy. Therefore, NASA scientists use and recommend the Ir–40Rh thermoelement with the pure Ir thermoelement for maximum life in oxidizing atmospheres.

Recent experiences at Langley Research Center indicate that Ir-Rh and Ir wires should be handled in the as-drawn rather than the annealed state. Annealing creates a brittleness in wires because of recrystallization; the calibration of the themocouples is not appreciably influenced when the wires are in the as-drawn state.

Extension wires for the Ir-Rh/Ir thermocouples are produced from copper and 347 stainless steel. The Standards Section at Langley Research Center calibrated the Cu/347SS thermocouples to 800° F. They report that each spool of Cu/347SS wire requires its own calibration. The calibration curve for this combination does not perfectly match that of the Ir-40Rh/Ir thermocouple; hence, for accurate measurements, temperature measurements of the extension wire-thermocouple wire connection are required, and a correction emf must be added to the thermocouple's emf.

REFRACTORY-METAL THERMOCOUPLES: TUNGSTEN-RHENIUM THERMOELEMENTS

Refractory metals are used as high-temperature thermocouples because of their high melting points. The metals of principal interest for such applications are molybdenum, tantalum, rhenium, and tungsten. Of this group, only the tungsten and rhenium metals are commonly used as thermoelements. Molybdenum has a very low thermal emf and even a polarity reversal with tungsten; thus, it is generally not used. Tantalum is not used since it is reactive at high temperatures with most materials used for thermocouple insulators.

Probes with W/W–26Re and W–5Re/W–26Re thermocouples are used by nearly all NASA research centers. Two such probe developments (refs. 19 and 20) will be discussed later in this chapter. The metallurgical characteristics of tungsten and rhenium alloys to 30 percent indicate that the alloys have melting temperatures above 5400° F and can be produced as fine wires, since they form terminal solid solutions. One principal disadvantage of the W/W–Re thermocouple, the brittleness of the tungsten wire, can be reduced by the use of W–Re alloy for the positive thermoelement. The W–5Re/W–26Re thermocouple has been used as a result of studies following this approach (ref. 20). This thermocouple has a higher thermal emf at low temperatures but a lower emf at higher temperatures than the W/W–26Re thermocouple. The positive thermoelement, W–5Re, is not as difficult to handle as pure tungsten and the welded thermal junctions have longer life in equipment subjected to vibration. Otherwise, the two thermocouples have nearly the same characteristics.

Junctions of the W and W–Re thermoelements may be formed by capacitor discharge methods or inert gas arc welding. Although the alloy thermoelements have slightly greater ductility than does the tungsten thermoelement, the thermocouples must be handled with extreme care.

These thermocouples have the following advantages:

(1) Melting point above 5400° F

(2) High thermal emf to 5200° F and higher

(3) Chemical stability at high temperature in vacuum and inert gas atmospheres

(4) Relatively low vapor pressure of materials.

NONMETALLIC THERMOCOUPLES

Many problems associated with the use of metals and metal alloys in high-temperature thermocouples could perhaps be avoided if carbon and/or carbides could be used as either one or both elements. Although little has been done to develop nonmetallic thermoelements, they show promise for certain high-temperature applications.

An MSFC-sponsored program at the National Beryllia Corporation investigated nonmetallic thermocouples capable of operating in an oxidizing atmosphere at high temperatures (ref. 21). This program was a materials study as well as a development effort to produce a thermocouple probe for measuring temperatures up to 5400° F when it is subjected to an erosive environment and high stress levels in the oxidizing atmosphere. These requirements are much the same as those for which W/W–26Re probes were developed by MSFC (ref. 19); however, the approach taken on this program was the investigation of all-ceramic thermoelements.

In selecting materials for nonmetallic thermocouples, the requirement of 5400° F operating temperature eliminates many candidate materials. Twelve materials with melting points over 5400° F were evaluated.

Tests were conducted at National Beryllia Corporation to study the thermoelectric output, electrical resistivity, and oxidation resistance of the various materials and their compatibility with other materials and environments. Thermocouple probe designs also were evaluated. The resulting probe designs are shown in figure 6. The thermal junction was formed by sintering together discs or rods of the two materials. The thermoelements were then cut by abrasive wheels to the configuration shown.

Tests on the materials indicated severe oxidation even at temperatures below 3000° F. Only one specimen, ZrB_2, retained its shape and integrity. Compatibility tests showed that both BeO and ThO_2 ceramics could be used in contact with ZrB_2 in air or vacuum at temperatures up to 3630° F, the limit of the compatibility tests. On the basis of preliminary studies, only the ZrB_2/ZrC combination shows promise as a high-temperature thermocouple.

HIGH-TEMPERATURE INSULATION MATERIALS

The selection of an adequate electrical insulation is a difficult problem in the design of high-temperature thermocouples. The insulation must prevent electrical shorting of the thermocouple circuit at the operating temperature and must not react with the materials of the thermoelement.

The most widely used insulating materials are beryllia (BeO) and magnesia (MgO) with melting points at 4620° and 5070° F, respectively. BeO has the highest resistivity of all the known insulators for high-temperature thermocouples. Actual resistances of BeO and MgO insulators in a test probe are shown in figure 7. Because of limited data for BeO, new resistivity data were generated to 4800° F (ref. 14) on Project Rover, the nuclear rocket engine program of NASA and AEC (fig. 8).

If the resistance of a thermocouple insulation is not sufficiently high at the operating temperature, the insulator acts as a shunt and generates erroneous readings known as "hot zone" errors. The hot zone errors can be deter-

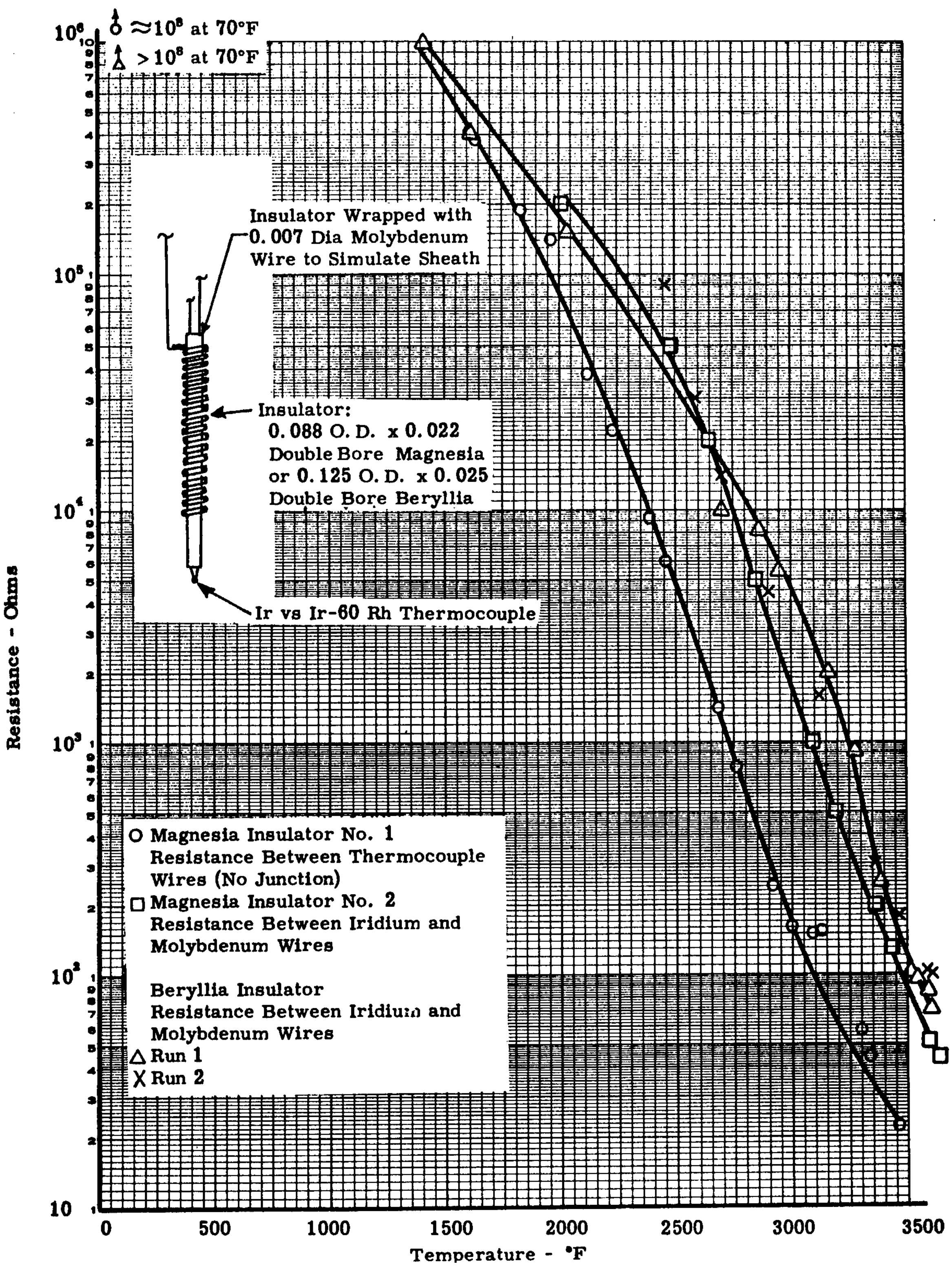


FIGURE 6.—Probe designs used in evaluating nonmetallic materials for a thermocouple capable of operating at 5400° F in oxidizing environments.

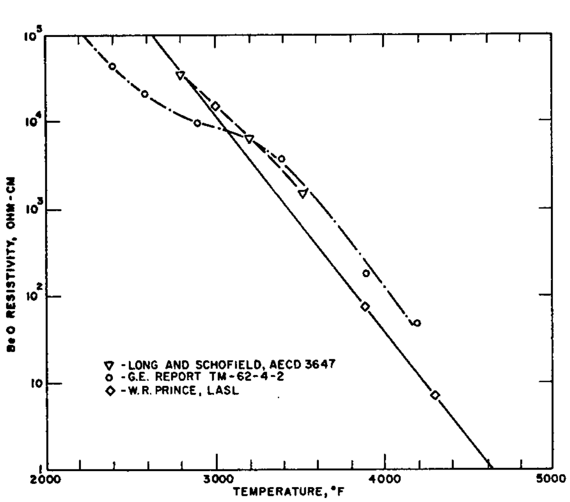


FIGURE 7.—High temperature resistance of thermocouple insulators as a function of temperature; information used in design of the thermocouple probe for Saturn booster rocket gases.

mined by considering the thermocouple circuit as a dc transmission line; the thermal junction is a generator with internal resistance. The circuit also contains distributed voltage sources along its length, distributed series and shunting components of resistance along its length, and an infinite impedance lead across the receiving end at null balance. This thermocouple circuit was analyzed (ref. 14) with a digital computer for the numerical solution of the differential equations of the circuit. Both coaxial and parallel conductor thermocouples were analyzed. Results from this analytical study show that temperature errors of over 1000° F can be encountered when the resistance of the insulator drops to low values at high temperatures. The drastic effects of shunting errors in high-temperature thermocouples were confirmed experimentally on Project Rover.

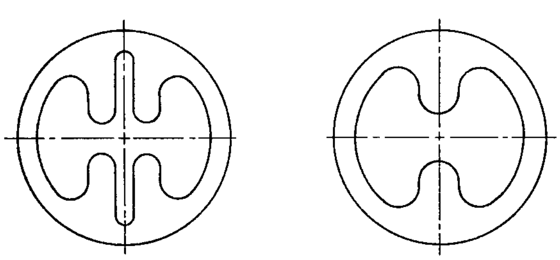


FIGURE 8.—Recent electrical resistivity data for BeO at high temperatures.

One result of the continuing research with high-temperature thermocouples was the development of the "Batman" insulator configuration (fig. 9), on Project Rover at Los Alamos Scientific Laboratory for NASA's Space Nuclear Propulsion Office (ref. 23). This insulator greatly increases the path for electrical leakage between the thermoelements in a probe. The thermoelements are loosely held in the insulators so they make contact with the BeO insulator at only a few locations. Other configurations are being studied in a current program.

Contamination and compatibility of the refractory thermoelements by BeO and ThO_2 insulators at high temperatures were reported on a program for the NERVA reactor engine (ref. 24), an engine being developed for NASA by AEC. Wires of tungsten, tantalum, molybdenum, and W–26Re alloy were wrapped around BeO and ThO_2 cylindrical specimens. These were then heated in evacuated tantalum capsules to various temperatures. It was found that molybdenum reacts with BeO at 4250° F

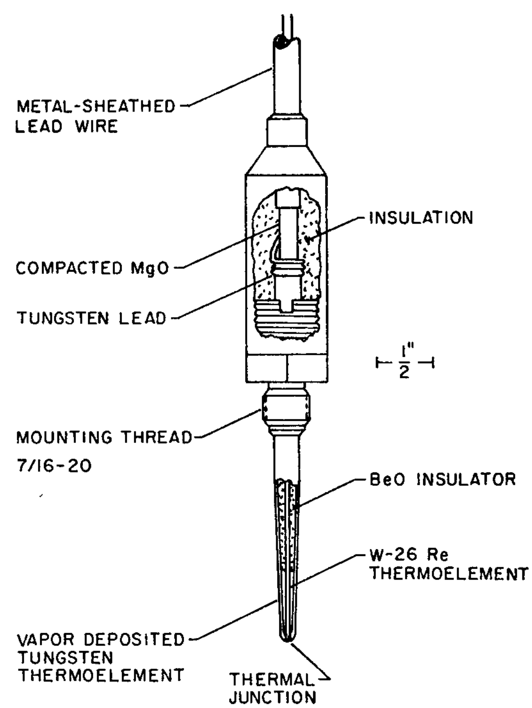


FIGURE 9.—"Batman" insulator configurations used on Project Rover to increase the electrical conductance path in thermocouple probes; material dense BeO and 76-mil diameter.

but tungsten does not. At 4450° F, about 200° F below the melting point of BeO, the tungsten, tantalum, and W–26Re wires react slightly with BeO. In all the tests with ThO_2, the various metals showed relatively good compatibility with it for 1 hour at 4450° F. Additional studies were described as in progress on the carbon diffusion rates in the four metals when various coating combinations were used as diffusion inhibitors.

GUIDES FOR THERMOCOUPLE MATERIALS SELECTION

The major considerations in selecting thermocouples for high temperature uses are operating temperature, environment, stability, durability, and cost. The thermocouples for operation above 3000° F are very limited in number; they consist of the noble metals, refractory metals, and nonmetallics. The type of environment further limits the thermocouple combinations that can be used. The stability and durability considerations are primarily influenced by the design of the thermocouples. Cost may be the deciding factor as to whether or not a particular thermocouple is used, or if one is used at all. Certainly all of the factors must be known in any application. Although there is no prescribed step-by-step procedure adequate for high-temperature thermocouples, the following example can be used.

The objective of a program conducted by Auto-Control Laboratories, Inc., for MSFC (ref. 19) was to develop a thermocouple probe that could operate at 5400° F when subjected to high stress levels in an erosive and oxidizing environment. The operating conditions are typical of those in a high-velocity, high-temperature gas stream in a rocket engine.

The probe design incorporated a tungsten sheath and a coaxial W–26Re center conductor. To accommodate mounting specifications, the probes were fabricated in a cylindrical form with a semilogarithmic taper as shown in figure 10. A study was conducted to ascertain the optimum materials for use as a protective coating to prolong the oxidation resistance of the probe. Tungsten disilicide and silicon oxide were selected as the best available materials. Such coatings were found to prolong the life of the probe by as much as an order of magnitude over the uncoated tungsten sheath, but it was concluded that no available coating was entirely satisfactory for long-time service.

Compensated lead wires were tested, but they introduced spurious emf's unless limited to use in areas where the temperature did not exceed approximately 212° F. Therefore, the later generation designs used extension wires of the same materials as the thermoelements.

No satisfactory high-temperature potting and sealing materials were available. Organic- and inorganic-filled epoxies and refractory cements failed at the high test temperatures. The thermal expansion coefficients of glasses were not compatible with the other probe materials. Sealing was accomplished by using an all-welded construction and bringing the oxide-insulated lead wires out through a stainless-steel tube to an area where the temperature was sufficiently low for use of conventional sealing materials. The base of the probe was compacted with finely divided magnesium oxide.

The tungsten sheath was formed by a thermochemical process. A mandrel was machined from mild steel to the inside dimensions of the sheath. A W–26Re wire was placed through a longitudinal hole in the mandrel and the latter was crimped around the wire. The assembly was then placed in a quartz tube and heated by induction. Vaporized tungsten hexafluoride (WR_6) was then introduced into the quartz tube as the mandrel was rotated. The tungsten deposited on the mandrel to the desired thickness, forming both the sheath and the thermocouple junction. The assembly was then immersed in hot concentrated hydrochloric acid, which dissolved the mild steel mandrel. In most cases no finish machining was required.

POTENTIAL INDUSTRIAL APPLICATIONS

Potential industrial applications of thermocouples capable of measuring temperatures above 3000° F fall into a number of categories. Each industry has peculiar requirements in addition to that of high-temperature service.

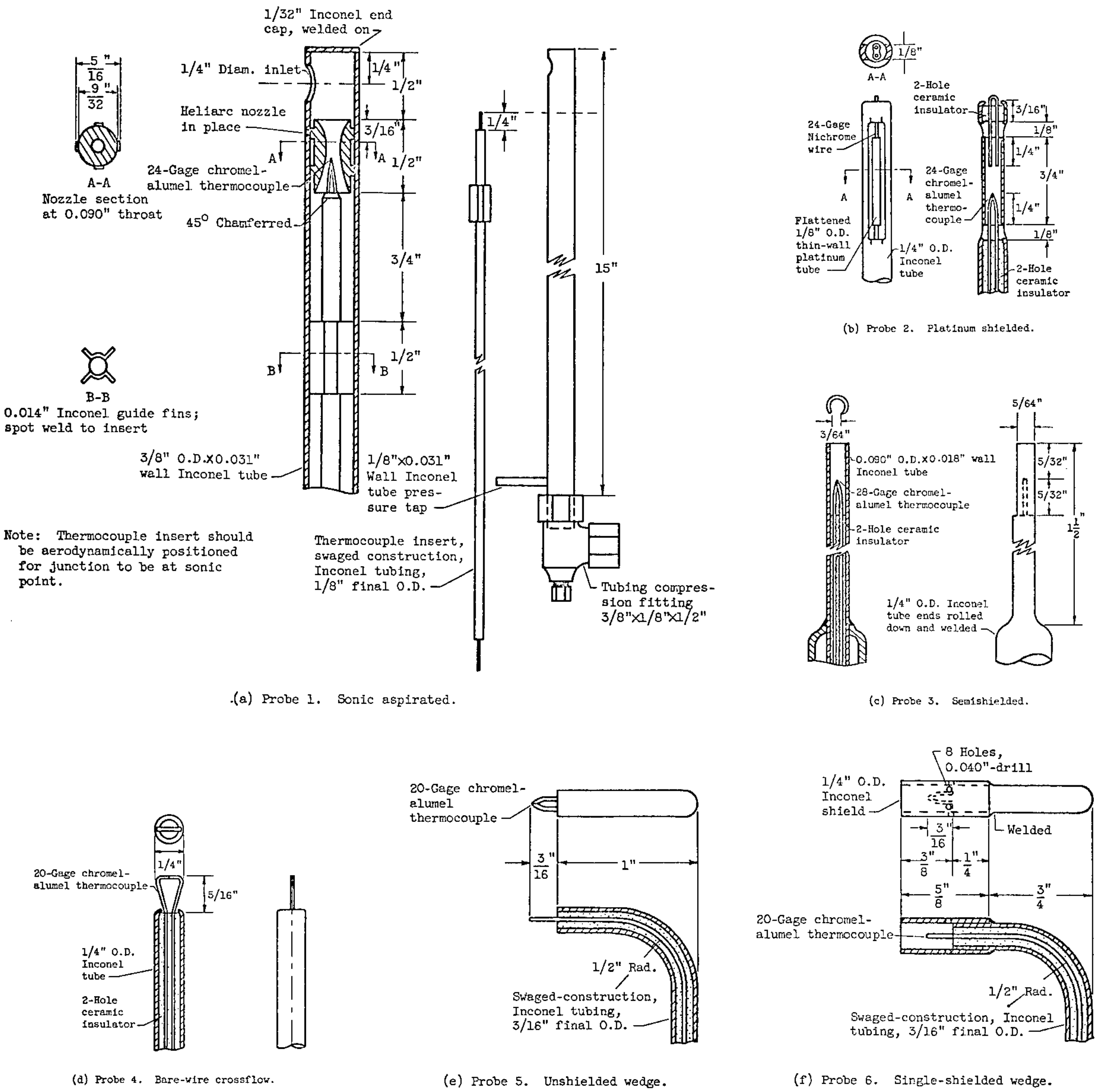


FIGURE 10.—Temperature probe of W/W-26Re coaxial thermoelements typical of the results from programs for developing high temperature thermocouples.

Ceramic Industries

Several high-temperature operations are used to manufacture items from the raw-material state. The same coaxial thermocouple mentioned above could be used for improved temperature control because of its rapid response to temperature changes. Sintering of a ceramic part at a more accurate and controlled temperature would produce an item of superior quality with less distortion. Thus, expensive final machining might be eliminated or at least reduced.

Manufacturers of lightweight ceramics for thermal insulations can produce more uniform insulations with improved temperature measurements and controls. The coaxial thermocouple or a two-wire variety with the batman insulator can provide more accurate measurements than some of the conventional high-temperature thermocouples. Such applications might mean greater profit to manufacturers of ceramics.

Process Industries

Industries that manufacture and synthesize materials from petrochemicals or other raw materials are developing new products that require higher reaction temperatures. The experience of NASA centers with the Ir–Rh/Ir and W/W–Re thermocouples and BeO thermocouple insulators for temperature measurements above 3000° F can be helpful to chemical engineers in the design of their systems. The refractory metal coaxial thermocouple described on the previous pages is capable of operation to 5000° F and higher; it could be used directly in a process gas stream and would have a rapid response to bring about improved temperature control of the process.

Metal Industries

The industries that prepare metals have some of the same problems of temperature measurement as the ceramic industries. However, the environments used by the metals industries create limitations different from those of the ceramic industries. The two-wire W/W–26Re thermocouple with batman BeO insulators and an inert protective sheath could provide accurate measurements at temperatures to above 4000° F. It could replace graphite/tungsten thermocouples that have been used for years by the metal industries to measure the temperatures of molten steel, but which are brittle and have relatively short life.

Aerospace Industries

Specific thermocouple designs such as those described in the next chapter should be of major interest to engineers who are working on rocket engines for military purposes.

CHAPTER 4

Thermocouples for Measuring Gas Temperatures

The measurement of total gas temperatures* presents problems that are generally more difficult to overcome than those encountered in the measurement of solid and surface temperatures. A thermocouple can indicate only the temperature of the thermocouple junction. The degree to which the temperature of the junction approximates the true temperature of its environment depends upon the exchange of energy between the thermocouple and the surrounding media. Furthermore, the temperature of a thermocouple junction in a gas stream is influenced by radiation and conduction to and from the thermocouple and by energy conversion and heat transfer in the boundary layer around the thermocouple. The design parameters considered in the development of a particular thermocouple for a system must be enumerated in a thorough analysis of that system. These parameters include gas velocity, temperature and composition, and enclosure dimensions and temperatures. This analysis of a system can be aided by reviewing references 25 and 26.

Two approaches can be taken in the design of probes for accurate gas-temperature measurements. First, a bare-wire thermocouple can be used and the indicated temperature corrected for environmental effects, such as radiation losses. The correction requires a reasonably thorough knowledge of the environmental conditions. Secondly, the junction environment can be changed to reduce or stabilize the errors. This change requires a probe design in which the conditions of the gas stream immediately surrounding the junction and other environmental factors are modified to reduce the errors to acceptable levels.

This chapter will describe three categories of special NASA thermocouple probes and their development, including bare thermocouples, shielded thermocouples, and thermodynamic probes. A general procedure for designing gas-temperature probes will be described, and some possible industrial applications suggested.

SPECIAL NASA PROBES AND THEIR DEVELOPMENT

Several NASA centers and their contractors have made significant contributions to the state-of-the-art in thermocouple technology for measuring gas temperatures. Among these are developments of Lewis Research Center; its scientists are considered authorities in this specialized area of instrumentation. A primary objective at Lewis has been the measurement of the gas temperatures of air-breathing propulsion engines. This objective limited some activities to the base- and noble-metal thermocouples capable of operating in oxidizing atmospheres. Efforts also have been devoted, however, to measurements of rocket exhaust-gas temperatures.

Many of the development programs at NASA centers are still active; consequently, results of performance tests of the probes are not yet available.

Bare-Thermocouple Probes

The most common design of a thermocouple for gas-temperature measurements is the bare-wire configuration. This category includes the

* Total temperature of a moving gas is the temperature of the gas in a static condition plus the temperature equivalent of its velocity energy.

configuration of two thermoelements extending into the gas stream where their junction is formed. The metal-sheathed thermocouple probes are also placed in this category, along with the special coaxial thermocouples where one thermoelement encloses the second.

In efforts to define the errors associated with the operation of the bare-wire thermocouples, Lewis Flight Propulsion Laboratory evaluated a number of them during the early and mid-1950's (refs. 27 to 30). The first program was related to the compromise between ruggedness and accuracy when the probe was operating in jet-engine exhaust gases. The studies (ref. 28) disclosed the results of exposing bare Pt-Rh/Pt thermocouples to these gases. Contamination was not a problem because the thermal emf of the thermocouples remained within the ISA tolerances (± 5 to 1000° F and ± 0.5 percent from 1000 to 2700° F). The source of errors with these thermocouples was the uncertainty of the increased emittances of the surfaces. The last two studies (refs. 29 and 30) were concerned with determining the errors in measuring temperatures of high-velocity gases. These works are the foundations on which more recent probe designs have been based. Because many probes of the Lewis designs are currently being used, the various configurations and their dimensions are shown in figure 11.

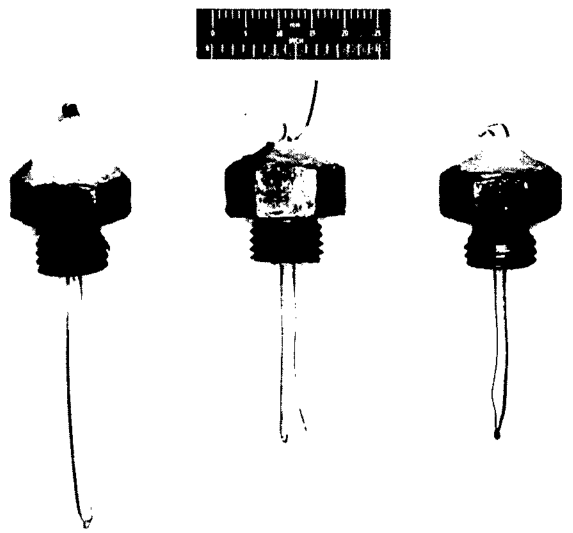


FIGURE 11.—Typical probes used in studies to determine performance characteristics and Nusselt numbers in high velocity air streams.

Bare-wire thermocouples which are successfully used at Langley Research Center for gas-temperature measurements are shown in figure 12. These Ir–40Rh/Ir thermocouples also vividly demonstrate iridium oxidation. The three thermocouples shown have been operated in the Center's 7-in. Mach 7 facility; they measure stagnation temperatures in the combustion chamber of the tunnel. They are exposed to air and combustion products of propane fuel at 3000 psia, at least 3000° F and a flow of less than 40 fps. These particular thermocouples have been exposed a total of 25 min. The wires were originally 20 mils; the Ir thermoelements of two probes have oxidized to failure and the third has nearly failed. The Ir–40Rh thermoelements still have their original diameters. Thermocouples of this design have been recalibrated after 20 min. of use. Each thermocouple was calibrated in a miniature 2500° F furnace designed to create a full gradient from the thermal junction to the mounting body, or a 1½-in. distance. The recalibration data matched the initial calibration data for the wire within ± 1 percent, the accuracy of the instrumentation for this particular calibration system.

The NERVA nuclear rocket engine is being developed by Aerojet-General Corporation for NASA's Space Nuclear Propulsion Office in cooperation with AEC. Westinghouse Astronuclear Laboratory is developing the reactor

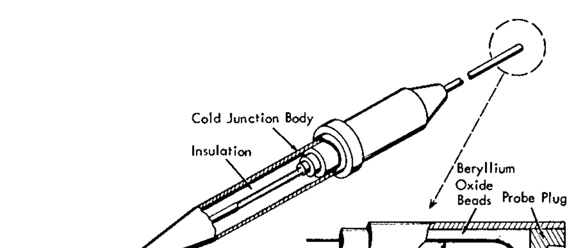


FIGURE 12.—Bare-wire IR–40Rh/Ir thermocouples used at Langley Research Center for gas temperature measurements in a 7-in. Mach 7 wind tunnel. Iridium wires have oxidized to failure when the probes were exposed to temperatures of 3000° F, accumulated 25 min for each thermocouple.

for NERVA. The development work on thermocouples at Westinghouse (ref. 24) has been described in the high-temperature section because a wide variety of metallurgical studies are being conducted on the refractory metals in an environment of carbon and high-pressure hydrogen.

The requirements of the thermocouples used in the NERVA engine are somewhat different from those for the control of the reactor. The control of the engine power during flight depends on measuring the temperatures of the hot hydrogen gases after they leave the reactor but before they pass through the rocket nozzle. The development of a suitable probe for measuring these gas temperatures has been under way for some years (ref. 31).

The specifications for the thermocouple are:

(1) Physical size: pass-through-hole 145-mil diameter
(2) Temperature range: $-100°$ to $4500°$ F
(3) Vibration: 20 g's at 5- to 2000-Hz frequency
(4) Pressure: 0 to 1000 psia
(5) Nuclear exposure: gamma 3×10^{10} ergs/cm(C)-hr and neutron 4×10^{16} nvt.

The small thermocouple diameter required in this installation limits the thermocouple stem length because of the low strength of the stem and the high side forces imposed on the thermocouple from the high velocity gases. Coaxial designs were considered initially; one thermoelement was the center wire and the second thermoelement was the coaxial (and exposed) tube. The coaxial thermoelement was W–26Re drawn tubing in one series of tests and vapor-deposited W sheath in another; W and W–26Re were the center wires, respectively. The first probes had cracks at the welded transition joint between the W–26Re tube and the steel housing used for the thermocouple mount. The second coaxial design proved to be too susceptible to stress fatigue; hence, no further development effort was devoted to the coaxial design.

A two-wire probe design was the final one selected for field testing (see fig. 13). It is a W–5Re/W–26Re thermocouple protected in W–26Re sheath with the thermal junction

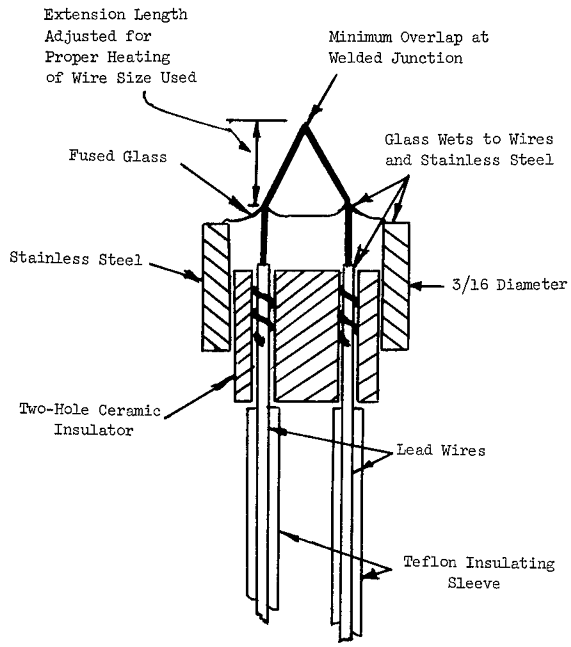


FIGURE 13.—Thermocouple probe for measuring hot hydrogen gases in the NERVA nuclear rocket engine.

formed by wedging the thermoelements against the inside of the sheath by a W–26Re plug and welding the plug in place. An optical pyrometer was sighted on the small hole in the end of the plug for calibration purposes.

Four of these two-wire sheathed thermocouples were field-tested in a NERVA engine. The indicated temperatures were 300° to 400° F below the calculated maximum temperature (approximately 3500° F). The difference between indicated and calculated temperatures was caused by stem heat conduction, radiation losses, low recovery factor, and shunting effects of the BeO insulators.

Bare thermocouples using a new concept for the measurement of transient temperatures in an expanding fireball are being developed by Midwest Research Institute under contract to MSC (ref. 32). For such an application, the temperature sensor must have a rapid response and be able to withstand the forces, temperatures, and oxidizing conditions of the blast environment. Fine-wire thermocouples were selected as the temperature sensors that could provide the most rapid thermal response consistent with adequate mechanical strength. They also require only simple associated electrical circuitry.

This new concept of measuring transient temperatures is based on preheating the thermal junctions of the thermocouples to a temperature near the anticipated peak temperature of the expanding fireball. The preheated thermal junctions permit larger wires to be used to withstand the shock forces of the fireball and yet have low enough thermal capacity to provide adequate time response. Preheating is done by applying a dc voltage to the thermocouple leads. Six thermocouples, each preheated to a different temperature, are used to bracket peak transient temperatures. Thermocouples preheated to a temperature below the peak transient temperature will indicate an increase in temperature as the flame front of the fireball passes, and those preheated to a temperature above the peak transient temperature will show a temperature decrease. One of the principal problems in determining gas temperature from a thermocouple reading is the selection of the proper value for the convective heat transfer coefficient, h. This problem is especially severe in the case of a fireball because of the widely varying properties of the gases and the turbulence of the flow. This problem is eliminated by the use of several identical thermocouples preheated to various temperatures.

The temperature probes have been tested with thermocouple elements constructed by both W–Re and Ir–Rh alloy wires in diameters from 2 to 6 mils. Several configurations of the thermocouple elements were tested; the one which was selected is shown in figure 14. The fine wires are welded to 10-mil lead wires which are cemented in a two-hole ceramic insulator. The fine wires are welded together to form an inverted 60-degree V. The lengths of the fine wires are adjusted to cause the highest preheat temperature to occur at the thermal junction. The thermal junction of the selected configuration protrudes into the hot gases; hence, the temperatures of gases are not disturbed by the holding structure. For thermocouples using W–Re alloy thermoelements, an inert atmosphere was provided for the thermocouple wires to prevent oxidation during preheat; a plastic film bag, maintained at a positive argon pressure, enclosed the thermocouple probes. Although a continuous purge allowed operation of the smallest (2 mils) W–Re thermoelements, the rate of oxidation for all the W-Re wires was high enough so that the number of preheating cycles for adjusting preheat temperatures was severely limited.

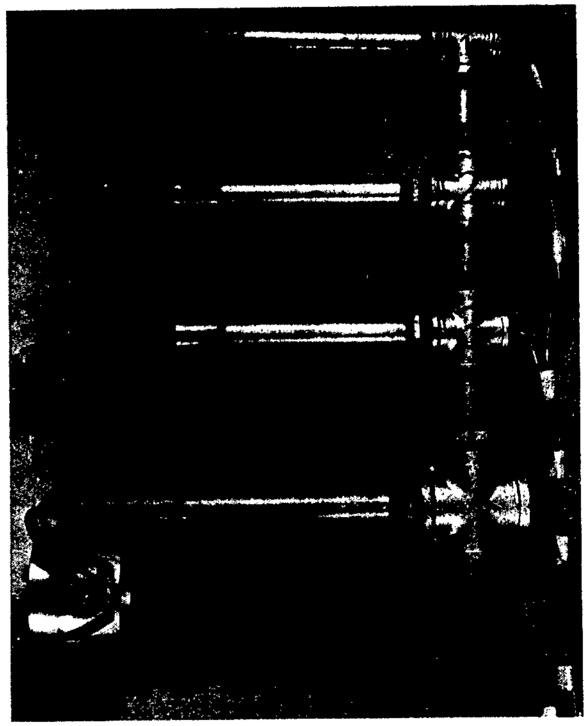


FIGURE 14.—Fine-wire thermocouple element used in a six-thermocouple array for measuring gas temperatures of fireballs.

Three probe designs were tested only for mechanical strength in a 25000-lb LOX–RP_1 blast test at Edwards Air Force Base (ref. 33). Each probe was equipped with the six preassembled Ir–Rh thermocouple elements (fig. 14) that had been soldered into recessed openings in the mounting bodies. The three probes, one of each design, were mounted in a test assembly with an aluminum foil switch unit (see fig. 15). The foil switch interrupted the dc current to the preheated thermal junctions when it was ruptured by the fireball shock front. The thermal junctions were preheated to six different temperatures between 3000° and 4000° F.

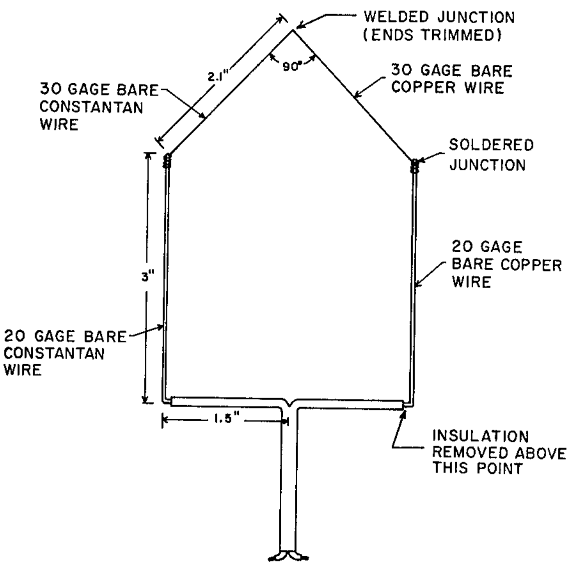


FIGURE 15.—Three 6-element probe designs tested for mechanical strength in 25 000-lb LOX–RP_1 fireball test; bottom assembly is aluminum foil rupture switch.

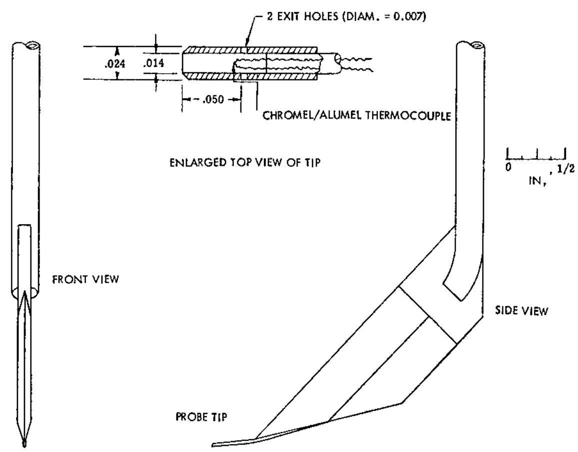


FIGURE 16.—Miniature shielded-thermocouple probe, 24 mils diameter, developed at Langley Research Center for boundary layer studies in wind tunnels.

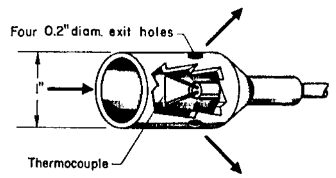
Shielded-Thermocouple Probes

Radiation shields increase the effective wall temperatures that are "seen" by the junction of a thermocouple and thereby minimize the radiation losses. Several shielded probes, shown in figure 11, have been studied at Lewis Research Center (refs. 29 and 30). The radiation errors were reduced by the shields, but the recovery corrections and time constants can be increased or decreased depending on whether the shield is a venturi or high recovery shield and whether the probe is an aspirated or unaspirated type.

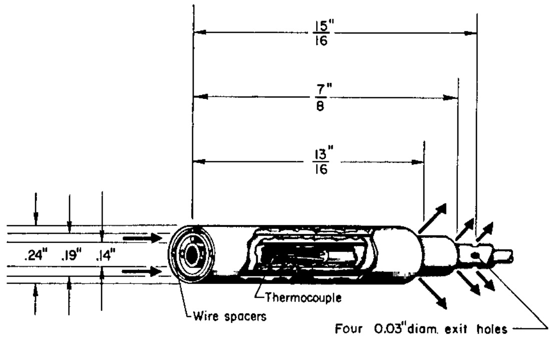
At Langley Research Center, numerous shielded thermocouple probes are used to measure gas temperatures in wind tunnels. These probes are designed for steady-state measurements; for example, tunnel runs of 45 min duration are possible in the 20-in. Mach 6 tunnel. A miniature probe, which is being used for boundary layer studies (ref. 34), is shown in figure 16. It is fabricated from 14-mil swaged Ch/Al thermocouple material. The thermal junction is formed by welding 1-mil wires exposed from the sheathed assembly. A 24-mil radiation shield with two 7-mil bleed holes is brazed onto the end of the thermocouple sheath. The variation of the probe recovery factor with Mach number and unit Reynolds number was determined in the Langley Unitary Plan wind tunnel; the recovery factors varied from 0.86 to 0.96. Smaller diameter probes have been fabricated and tested, but the results were not satisfactory.

A low-density wind tunnel at Langley uses special radiation-shielded thermocouples (ref. 35). The tunnel is a 12-in. hypersonic ceramic-heated blowdown wind tunnel with a free-jet test section. Stagnation temperatures may be as high as 3300° F. The static pressure range is from 15 to 120 microns Hg; consequently, thermocouple probes in the test section after the nozzle must operate in low-density and high-temperature gases. Several probes have been used in this chamber (figs. 17a and 17b); they provide large-area bleed spaces in their shields because of the low-density gases.

These thermocouple probes are also designed to minimize the radiation and conduction losses from the thermal junction; these losses are reduced by using small-diameter wires and having a large length-to-diameter ratio in the probe (fig. 17a). The fine wires are supported by a V-shaped configuration of the appropriate thermocouple wires; the thermal junction of the fine wires is halfway between the support wires. Because of the high stagnation tempera-



(a) Cold-shield temperature probe.



(b) Triple-shield temperature probe.

FIGURE 17.—Two radiation-shielded thermocouple probes used at Langley Research Center in a low-density wind tunnel.

tures, Pt–10Rh/Pt thermocouples are used. This probe has a cold-shield; i.e., the shield has sufficient mass that its temperature does not increase significantly during the time of the temperature measurements. With a relatively constant cold wall of the radiation shield, radiation errors can be accurately calculated. A typical probe with three radiation shields can be seen in figure 17b. The radiation errors are virtually eliminated because the probe is designed to operate with its inner shield at nearly the same temperature as the recovery temperature. The radiation shield of the probe is fabricated from a Pt–Rh alloy.

The performance of the probes in the low-density tunnel at Langley has not been entirely satisfactory. Since the publication of reference 35, additional knowledge has been gained that makes possible an improvement in the design of the original probes.

A molybdenum-shielded W/W–26Re thermocouple probe used at Langley and a multiple probe rake using nine of these thermocouple probes are shown in figure 18. The shield is assembled from molybdenum support spacers and 20-mil-wall tubes which are joined by

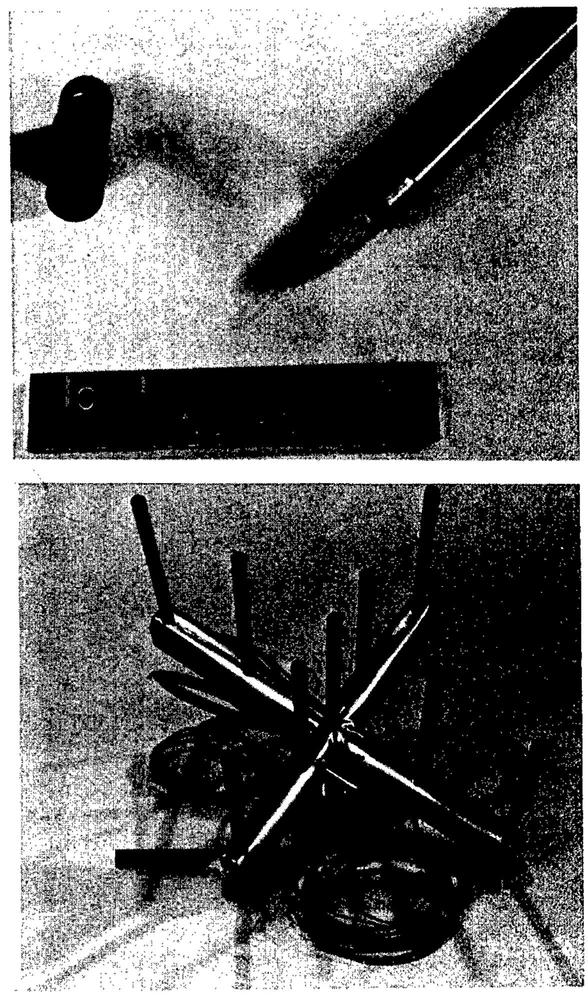


FIGURE 18.—Molybdenum-shielded W/W–26Re thermocouple probe and a rake with nine probes for wind tunnel temperature measurements at Langley Research Center.

electron beam-welding. The shield assembly is held by only a snug fit between the outer shield and the probe body; this mechanical fit enables the replacement of the W/W–26Re thermoelements when necessary.

Fast-response thermocouple probes have been developed by Rosemount Engineering Company under contract to MSFC for the measurement of total temperature in the gas generator systems of the F–1 and J–2 rocket engines (ref. 36). The probes were designed to measure temperatures in the 0° to 1500° F range continuously and up to 2700° F for 10 sec. Gas velocities ranged from 0 to 7000 ft/sec and gas pressures from 0 to 800 psig; the temperature of the structure on which the thermocouple was mounted ranged from 0° to 570° F. The specified time response was a 100-msec time constant for an indication of 63 percent of a step temperature change from room temperature to 400° F at 16 lb/sec gas flow in an 8-in. diameter pipe. Conventional temperature gages used in jet-engine tailpipes cannot withstand the temperatures and aerodynamic loads or meet the specified response characteristics.

Several factors were considered in the selection of materials for the thermoelements and the probe. First the gas atmosphere was established as one with high water vapor and free hydrogen content but one that would reduce few oxides. The permeability of various materials to hydrogen at the high temperature and pressure was also a factor. Adequate mechanical strength of the metals at high temperatures was required. High thermal-conductivity materials were desirable in the sensing zone to improve accuracy. Furthermore, a 100-msec time response was needed, requiring sensors with low specific heat. A low thermal-conductivity metal (AISA Alloy 680) was selected for the one-piece mounting stem to reduce heat conduction to the walls.

The selected thermoelements were Pt-10Rh and Pt; Pt–30Rh/Pt–6Rh thermocouples were considered because of the reduced long-term drift of this combination but could not be matched to the vehicle circuitry. W/W–Re thermocouples were not used because of their poor stability characteristics under cyclic conditions and the fabrication problems associated with tungsten. The final probe design is shown in figure 19. It was the result of several evolutionary designs in which the interior flow was progressively modified to obtain the desired response time.

Combined radiation and conduction errors were evaluated for three probes as a function of temperature at constant pressure, pressure at constant temperature, and wall temperature. For a high mass-flow rate, a time constant of 26 msec was measured; and for a low mass-flow rate, a time constant of 85 msec was obtained.

Marshall Space Flight Center also sponsored

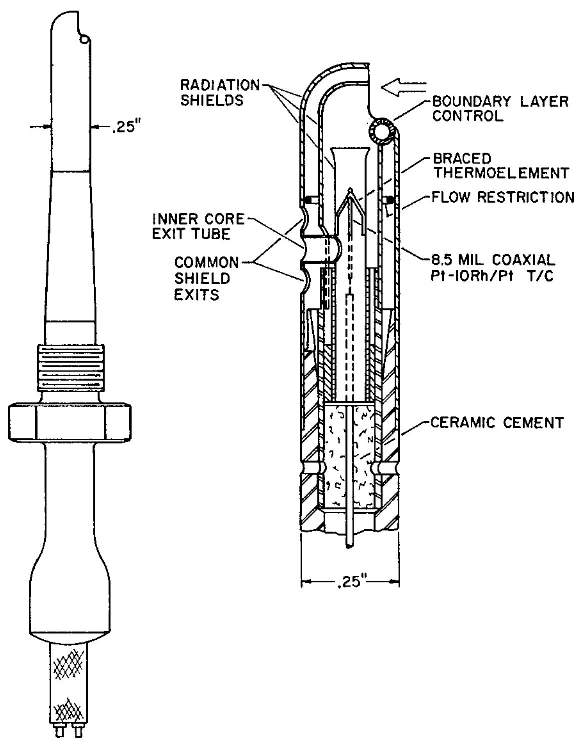


FIGURE 19.—A fast responding shielded-thermocouple probe with a time constant of 100 msec for operation to 2700° F in gas generating systems of rocket engines at MSFC.

the development of thermocouple probes at Southern Research Institute for measuring the temperatures of rocket-exhaust products in the skirt of the Saturn booster (ref. 22). The probes were required to withstand exposure to 3630° F for up to 20 sec and vibration levels up to 48-g acceleration at frequencies from 140 to 2000 Hz. The Ir–60Rh/Ir probe, which was developed during this program, is shown in figure 20. All exposed ceramic surfaces were coated with a silicone compound for waterproofing. This coating vaporizes when heated but does not leave an electrically conducting residue.

A major problem in the fabrication of the probes was embrittlement of the thermocouple wires in the vicinity of the junction after welding. This embrittlement resulted in a fragile thermal junction, but the junction withstood vibration tests. The same probe design was used for W–5Re/W–26Re thermocouples in an effort to develop a stronger unit (ref. 20). The

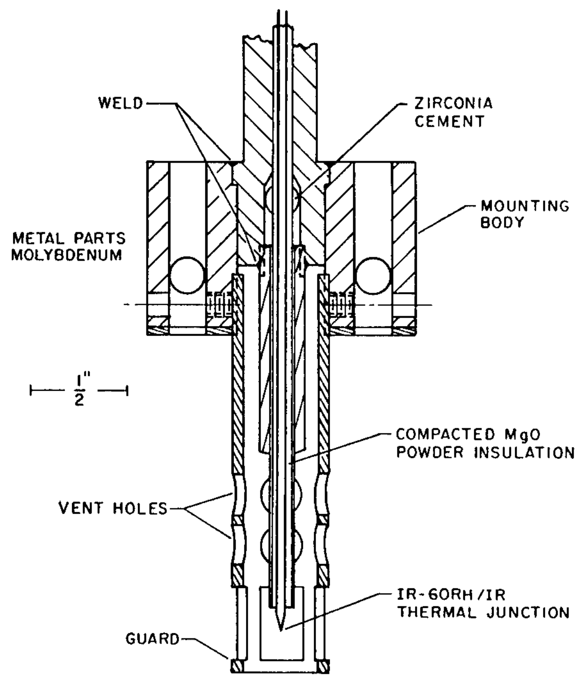


FIGURE 20.—A thermocouple probe for measuring the temperatures of exhaust products from Saturn booster rocket.

thermal junctions of the W/Re alloy wires were less brittle than those of Ir–Rh and Ir; thus, smaller junctions were possible with an improvement in the response time (from approximately 1.0 to 0.8 sec).

Thermodynamic Probes

Thermodynamic probes have been developed as a means of overcoming the effects of high-temperature and high-velocity gas streams on bare or shielded thermocouple probes. Basically these thermocouple devices make possible the measurement of the temperatures of gases previously unmeasurable. However, the properties of the gases must be known before gas temperatures can be calculated. Several thermodynamic probes were refined and evaluated by Lewis Research Center and earlier when the Center operated as the Flight Propulsion Laboratory. The probes discussed in this section are the pneumatic temperature probe, the cooled-gas pyrometer, the cooled-tube pyrometer, and a related enthalpy probe.

The pneumatic temperature probe consists of two nozzles in series through which a sampling of the hot gas passes continually and cools, as shown schematically in figure 21. The temperature of the hot gases is a function of the pressure measured at each nozzle, the temperature of the cooled gas at the downstream nozzle, and nozzle areas and coefficients. Thus, the total temperature of the gas stream can be computed if the thermodynamic properties of the gases in the stream are known. The theory and corrections for use of the pneumatic probe are presented in reference 37. Performance data are also given from tests in the Lewis high-temperature water-cooled tunnel with gas temperatures from 1000° to 3500° F.

Analytical studies at Lewis (ref. 38) considered the effects of the thermodynamic parameters on the pneumatic probe—in particular, the specific heat changes of the gases, and the effects of vibrational relaxation on the temperature measurements. When gas flows into the nozzle of the probe from the free gas stream, it reaches a partial static condition on the leading edge of annulus of the probe. It also accelerates as it enters the nozzle. There are rapid changes in the available thermal energy; consequently, a number of vibrational modes of thermal excitation are generated. The relaxation (response) times of these modes are so rapid that the modes cannot follow the changes in energy. Hence, the calculated critical velocity in the nozzle and the temperature are affected. The equations derived in the studies can be used to correct the measured parameters to obtain the gas temperatures. These equations are useful in the 1350° to 5000° F region and for Mach numbers between 0.3 and 2.0.

The cooled-gas pyrometer is another thermodynamic probe that uses a thermocouple for measuring temperatures of gases which have been cooled from their original high temperature state (fig. 22a). The successful operation of the probe depends upon determination of the change of energy of the gases as they are cooled. The theory and design of a cooled-gas pyrometer were developed at Lewis (ref. 39). Three probes were fabricated from the resulting design, figure 22b. The experimental results

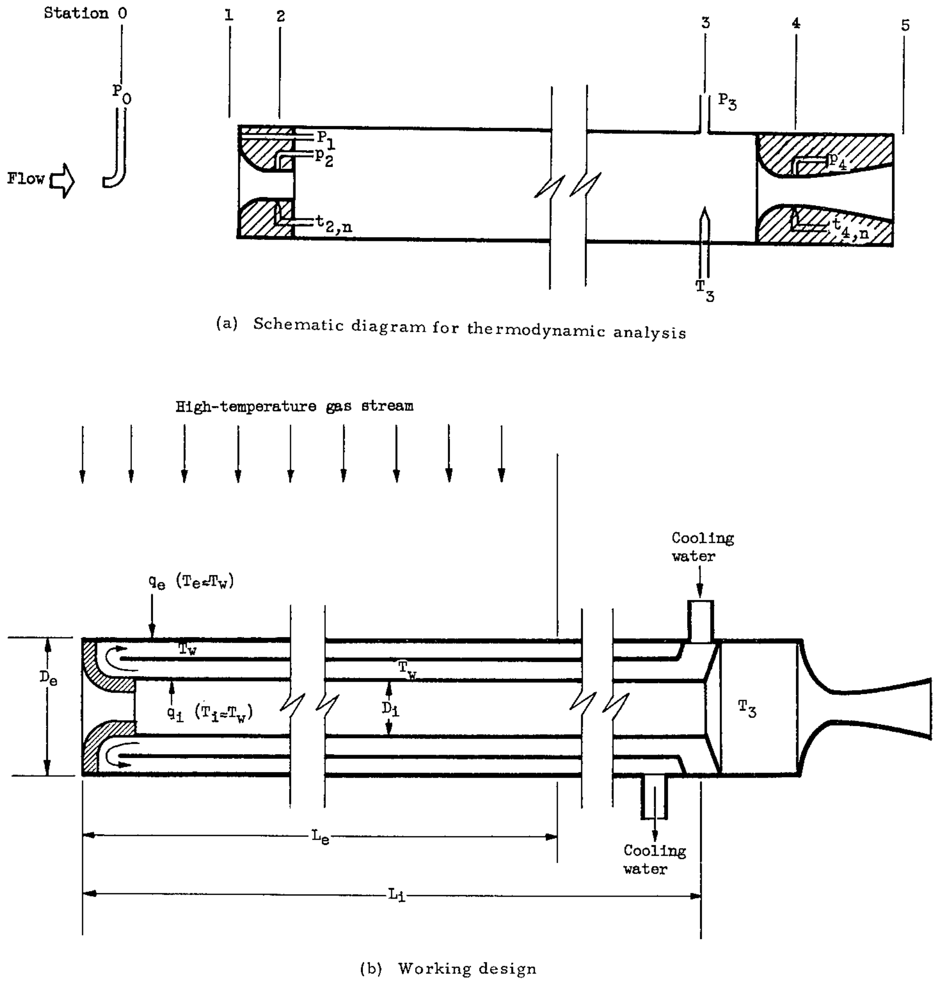


FIGURE 21.—Schematic diagrams of a pneumatic probe for determining gas temperatures.

indicate that the operation of the probes is relatively simple, but individual correlation curves and accurate gas property data are necessary for converting the data from the probes to gas-stream temperatures. The correlation curves must be obtained from an individual calibration of each probe. If accurate gas properties are not available, the probes can still be used for comparative temperature measurements such as temperature profiles.

The two previous probes operated on the basis of knowledge of the thermodynamic properties of gases. A third thermodynamic probe is the cooled-tube pyrometer developed at Lewis Research Center (ref. 40). This probe operates on the measurement of the rate of heat transfer from the hot gases to an exposed tube in the form of a loop seen in figure 23. Thermocouples measure the temperature rise of a coolant circulated through the exposed tube to determine the rate of heat transfer. The gas temperatures are calculated from the rate of heat transfer, the Nusselt and Reynolds numbers, the Mach number, certain properties of the gases, and a constant of proportionality. This constant is the relationship between the Nu and Re numbers and must be determined in a calibration run at some convenient temperature with a reference thermocouple or another thermodynamic probe.

A similar technique was developed at Langley Research Center (ref. 41), but the probe was a

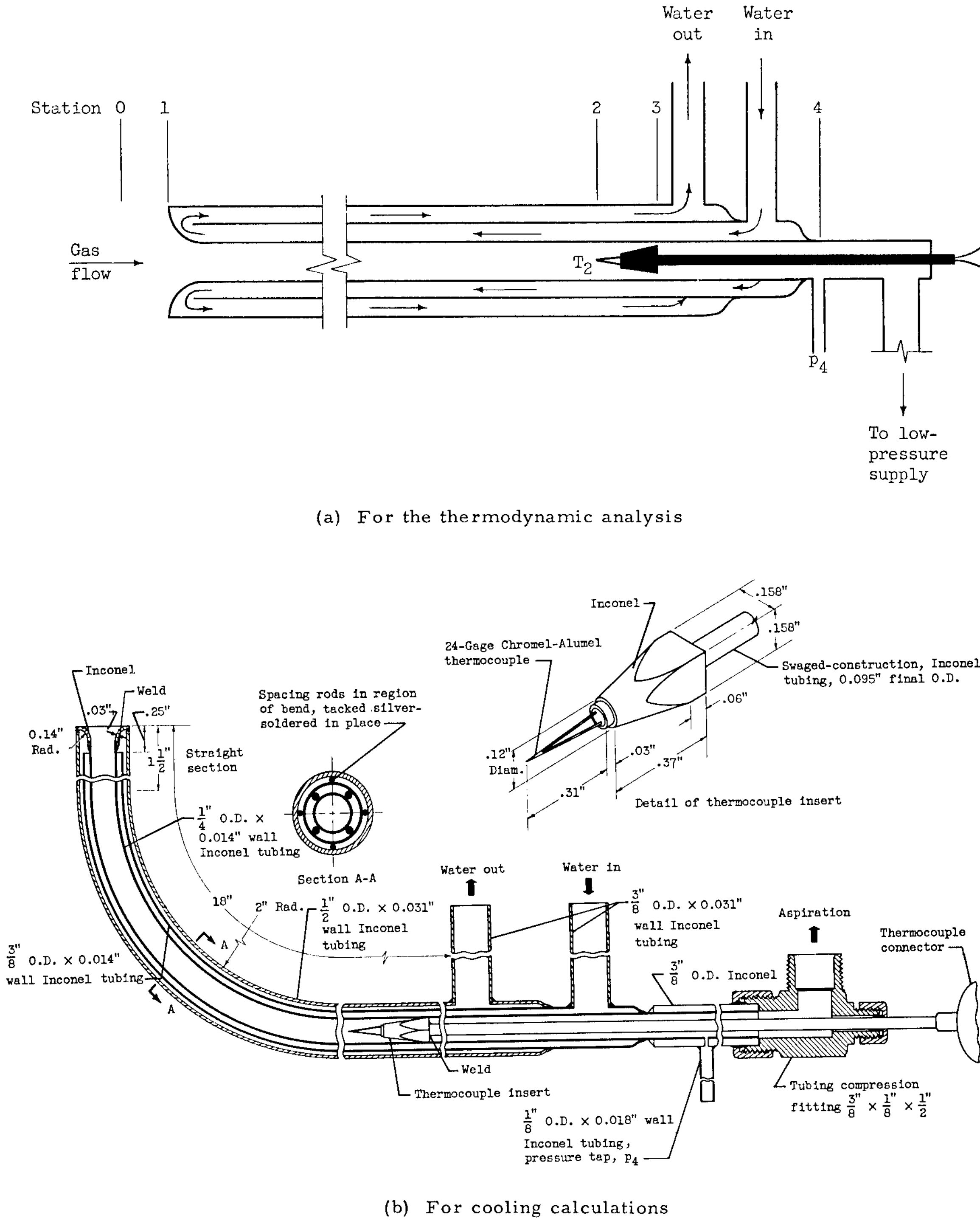


FIGURE 22.—Cooled-gas pyrometer for determining gas temperatures of hot, high-velocity gases.

cooled flat plate at the blunt end of a probe. Equations were developed to analyze the probe data to determine the temperatures of flames (approximately 7500° F). The results of this

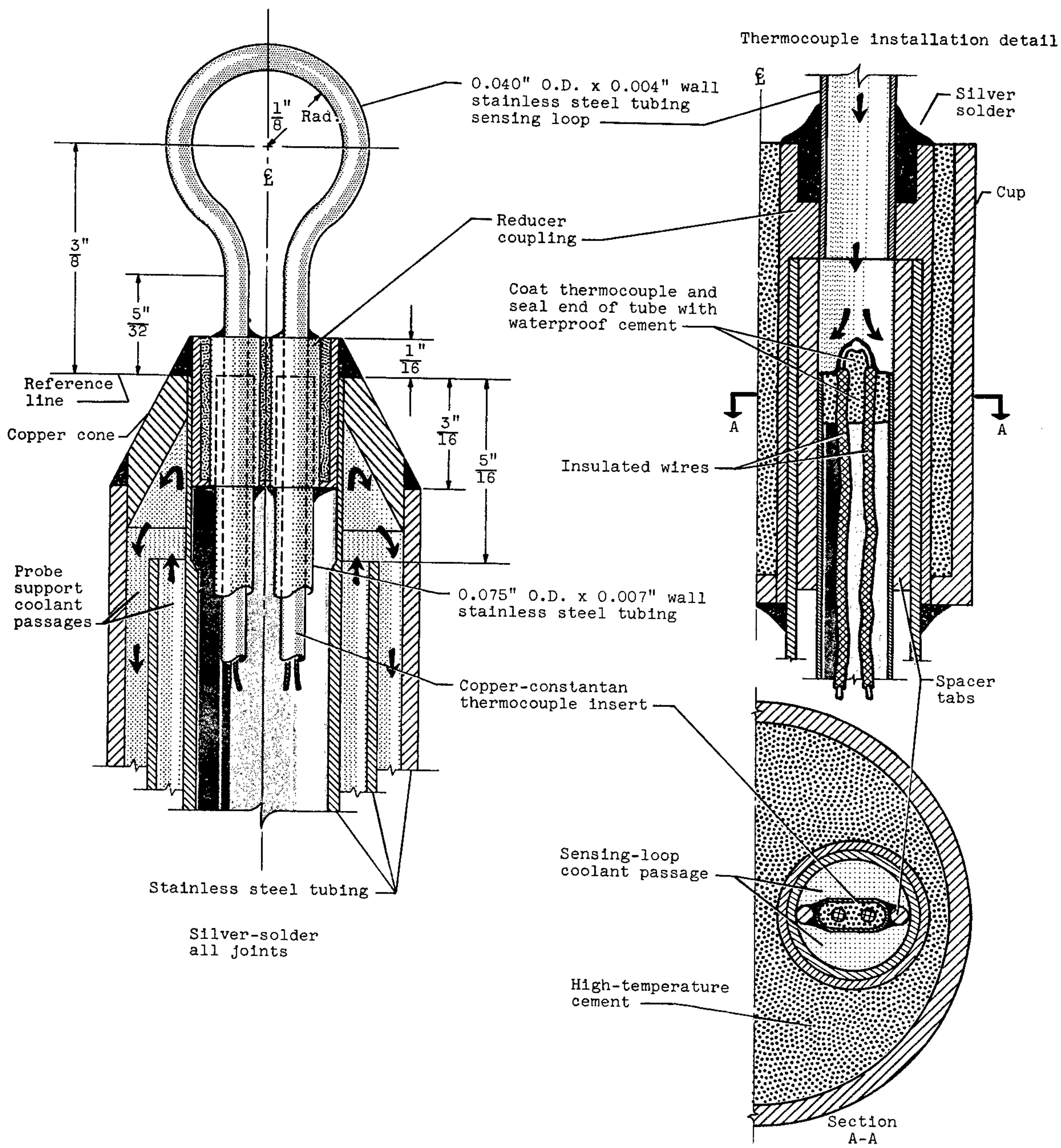


FIGURE 23.—Cooled-tube pyrometer for gas temperature determinations depending on knowledge of heat transfer coefficient between gases and probe.

particular experiment were within 3 percent of spectrographic and microwave temperature determinations.

The use of the thermodynamic probes to measure gas temperatures of rocket exhausts has been reviewed in reference 42. These probes have potential applications for measurements of gases in excess of 5000° F where most materials cannot survive. The question arises as to which probe is the most accurate for this type of gas-temperature measurement. Lewis made comparisons of six temperature probes or systems from 2000° to 4000° F and Mach numbers from 0.4 to 0.6 (ref. 43). The three thermodynamic probes were included in this group along with a shielded thermocouple and a bare wire thermocouple probe. The sixth probe was a sodium line-reversal pyrometer. The various instruments were exposed to the same conditions, and results of the measurements of each probe were compared to the mean of the others. The two thermocouples and the pneumatic probe had the least deviations from the mean values of the group; however, these results do not necessarily indicate their superiority. The selection of a probe for measurements in a high-velocity, high-temperature gas stream involves a number of considerations that must be thoroughly investigated before a selection is made.

In the very high temperature regime (above 4000° F), the thermodynamic properties may not be known, the gases may be dissociated, or the effects of relaxation may be uncertain. The use of the thermodynamic probes becomes invalid for temperature measurements. Useful information can then be expressed in terms of enthalpy. The cooled-gas probe is used as an enthalpy probe since the heat content of the high temperature gases is then being measured (ref. 44). An enthalpy probe used at Langley Research Center in an arc tunnel facility is shown in figure 24. This type of probe measures the energy of the gas stream instead of the temperature, and the signals from it are often used to control the power to the arc tunnel. Thus, the measurement of gas temperatures or of the effect of these temperatures (enthalpy) is a vital phase of NASA's testing facilities.

PROCEDURES FOR DESIGNING GAS-TEMPERATURE PROBES

The approach to the design of thermocouple probes for total temperature measurements in gas streams involves the reduction of errors to an acceptable level. This is done by producing an environment around the thermocouple junction in which velocity, conduction, and radiation errors are reduced to a level consistent with the accuracy desired in the temperature measurements. Detailed procedures for calculating these errors and designing probes are given in references 25 and 45 to 47. Basically, the velocity and radiation errors are reduced by radiation shields because the shields slow down the gases and increase the wall temperatures. Conduction errors are reduced by increasing the length-to-area ratio of the wires.

POTENTIAL INDUSTRIAL APPLICATIONS

The potential industrial applications of NASA-developed thermocouples designed for measuring gas temperatures are virtually unlimited. In most manufacturing operations or chemical processes involving the flow of a gas, the measurement of the gas temperature may be necessary. Although reliable temperature sensors now are used, there are probably many situations where improvements are needed.

The thermocouple probes which have been described are applicable for gas-temperature measurements from liquid hydrogen temperatures (−423° F) to above 5000° F. Some potential industrial applications of these gas temperature-measuring devices are enumerated below.

Electronics Industry

In the production of transistors and miniaturized circuits, several operations require furnace-firing of components in a controlled atmosphere. The measurement of the gas temperatures in the furnace could increase in accuracy if simple versions of the shielded-thermocouple probes developed by Lewis or Langley Research Center were used. Improvement of the time response would be achieved by the use of a shielded probe; hence, more accurate furnace-temperature control could be obtained, with a resulting saving.

Chemical Industry

The production of chemicals involves many processes in which gases are generated. The temperatures of the gases may be anywhere from the cryogenic region to the 4000 to 6000° F range. The plasma arc reactor has opened new possibilities for very high temperature reactions. The temperatures in these reactors are often 10 times higher than those in conventional reactors, and temperature measurements are not easily made. The enthalpy probes described

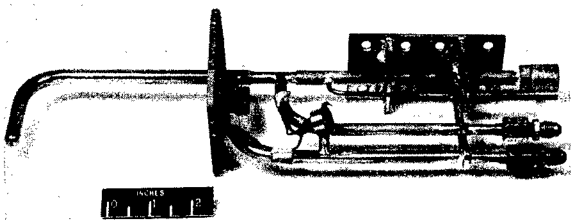


FIGURE 24.—An enthalpy probe used at Langley Research Center in an arc tunnel facility.

above may have direct application to this technology in the chemical industry.

Drying powdered chemicals by a hot gas is another possible application. A rapid-responding thermocouple probe could follow variations in true gas temperatures and make possible closer control than is obtainable with a slower-responding thermocouple. NASA probe designs and design procedures that would provide the desired response have been suggested in this chapter. Ammonia is manufactured in a high-temperature, high-pressure reaction chamber which combines nitrogen and hydrogen gases. The control of the temperatures must be precise for efficient operation. Gas-temperature measurement with the refractory metal thermocouples might be feasible, and these would replace thermocouples in protection tubes. The improvement in response time could make the process more efficient.

Petroleum Industry

The petroleum industry is concerned with measuring gas temperatures in fractionating columns, thermal catalytic units, reaction chambers, pipelines, and fuel-storage systems. Because thermocouples are widely used in these areas, the circuitry has already been installed. More sophisticated probes could be substituted wherever advantages are to be gained. In high-temperature chambers, columns, and units, thermocouples are often installed in protection tubes to prevent contamination and corrosion. If refractory metals with protective coatings could be used, thermocouples such as those developed for MSFC for measurement of rocket gases (ref. 19) might provide service without protection tubes. An advantage would be immediately gained in the improved time response of the bare-thermocouple probes. Another advantage would be lower conduction losses, which in turn would mean more accurate measurements.

The flow of natural gas in pipeline systems is often flagged by a slight temperature change of the gas. Purchasers of the gas may order natural gas with slightly different additives; hence, the shipment must be isolated and identified. By the use of a rapid-responding thermocouple rugged enough to withstand high momentary gas velocities, slight temperature differences can be measured. The slingshot thermocouple (ref. 12) has a direct application in this area of instrumentation.

Transportation Industry

Gas-turbine engines, now widely used in the turbines of jet aircraft, are being developed for large trucks. Measurement of gas temperatures in the combustion chambers with a bare-wire thermocouple probe or with a thermodynamic probe is a direct application of the NASA thermocouples. Temperature measurements with rapid-responding thermocouples of the type developed at Lewis and Langley would improve performance and minimize the length of time needed for engine acceleration.

CHAPTER 5

Thermocouples for Surface Temperature Measurements

The measurement of surface temperatures requires special considerations. The presence of a thermocouple can significantly influence the accuracy of the measurements by creating disturbances in the heat flow to and from the surface. These disturbances can cause the largest errors for thermocouples when they are used for measuring rapidly changing (transient) surface temperatures.

This chapter give the principles of operation for surface thermocouples and points out the importance of measuring surface temperatures. Special surface thermocouple probes developed in NASA programs will be described and their uses classified for either transient or steady state measurements. The procedure of selecting a particular thermocouple design will be outlined and potential applications in industry suggested.

PRINCIPLES OF OPERATION

All surfaces in space are boundaries of objects; at these surfaces the temperature may or may not be the same as that within the objects. Surface temperatures differ from the bulk temperature of the object when heat is transferred to or from the object. Hence, the main objective in the development of a thermocouple for measuring surface temperatures is to produce it in such a manner that the thermal junction and the leads create a minimum of disturbance to the heat flow at the surface. Transient surface temperatures exist when equilibrium conditions have not become established. Transient surface temperatures occur, for example, at:

(1) The heat-shield surfaces during the early phases of reentry of a space vehicle into the earth's atmosphere

(2) The exposed surfaces of a rocket nozzle during the first few seconds of the rocket firing

(3) The surfaces of a mold during the injection of molten metal in a die-casting operation.

As soon as ablation temperatures of the heat shield or the nozzle-liner material are reached in the first two examples, the surface temperatures become relatively constant; a thermal-equilibrium condition is then established at the surface. However, thermal equilibrium never exists during the die-casting operation because the molten metal solidifies and is cooled by the heat sink of the mold. Thus, the surface temperatures are constantly changing.

An important reason for measuring the surface temperatures of an object is the need to determine the quantity of heat being transferred to it. A measurable temperature exists between the surface and the interior of the object only when heat rates are relatively high and the thermal conductivity of the object is low. Numerous analytical procedures have been developed through the years to determine the heat-transfer rate from surface temperature data.

Another reason for measuring surface temperatures is that this measurement may be the only practical way to obtain the average temperature of a thin sheet or tube of a material. When relatively low heat rates occur in an experiment, the surface temperature will be virtually the same as the average value. Hence, bulk metal temperatures can be conveniently determined by measuring the surface temperatures.

SPECIAL NASA SURFACE THERMOCOUPLE PROBES

Generally, surface thermocouples are designed for either transient-temperature measurements or for steady-state measurements. When a thermocouple is used for transient measurements, the thermal junction must be well defined, parallel to the exposed surface, and very close to it. The reference junction may be relatively close to the thermal junction; in such instances, the duration of the exposure to heat must be sufficiently short that all the useful signal is obtained before the heat is conducted to the reference junction.

Measurements of steady-state temperatures may or may not require a precise location of the thermal junction. When the probe is used for steady-state heat transfer determinations, data analysis is usually based on the temperatures being known at the surface. However, if the thermocouple is being used for temperature measurements of a thin sheet or wall of a tube, the precise location of the thermal junction is not so important. Conventional thermocouple wires welded to the metal surface are a very common method of measuring the surface temperatures in this case. In steady-state measurements, extra care is needed to provide a stable reference base in the circuit.

Transient-Temperature Measurements

An unusual program was conducted at NASA's Ames Research Center to determine the heat transfer to ballistic models in air and CO_2 at velocities up to 18000 fps (ref. 48). This contribution to the advancement of the state-of-the-art involved a surface thermocouple built into the nose of a hemispherical model (fig. 25a) for one series of stagnation-heating experiments. In another series the surface thermocouple was formed around the conical surfaces of a model of the Apollo spacecraft (fig. 25b) for base-heating studies. The entire thermocouple circuit was built into these models, which were no larger than 0.3 in. in diameter. A cap or ring of 7.5-mil thick copper sheet was exposed to the hot gases; at the desired position, a constantan pin or washer was soldered to the copper to form the reference junction. The copper wire was looped near the periphery of the model four times and back to the exposed copper sheet to form an inductive coil. The magnetic field resulting from the thermocouple current flowing through the model coil induced a signal on stationary pick-up coils for data acquisition. The various elements of the experimental setup are shown in figure 26. The system operated successfully, and the data obtained had accuracies that compared favorably with those obtained in shock-tube measurement of heat-transfer rates. One of the advantages of this technique was that the signal was not deteriorated by the ionized gas sheet that surrounded the model in flight.

In the Radiation Research Branch at Ames

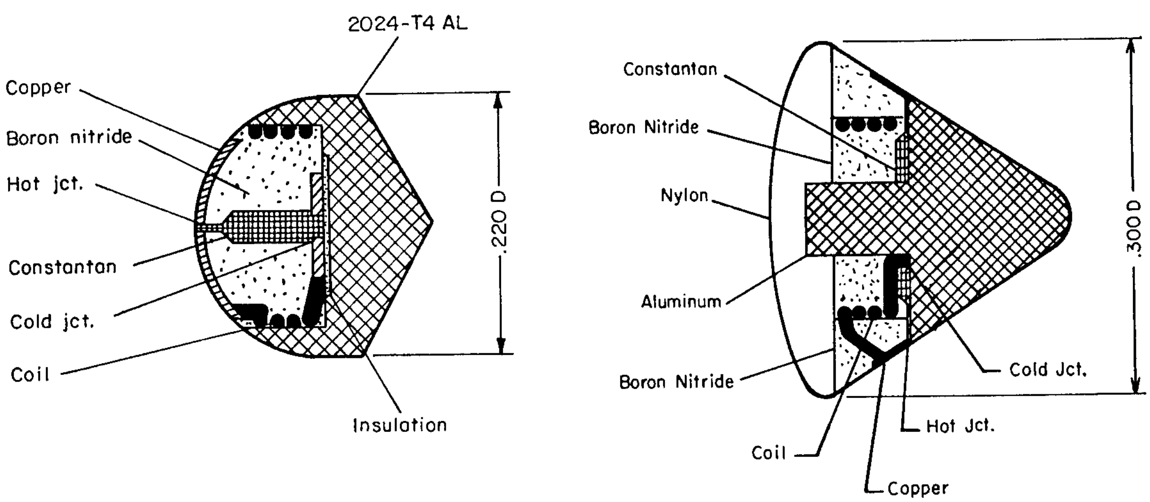


FIGURE 25.—Ballistic models: (a) hemispheric model (b) Apollo model instrumented with surface thermocouples to determine heat transfer at velocities up to 18000 fps.

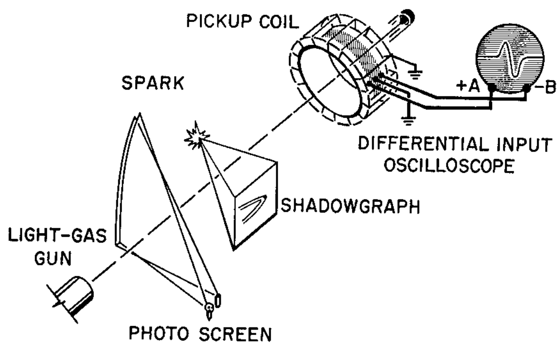


FIGURE 26.—Experimental setup to obtain surface temperatures of ballistic models.

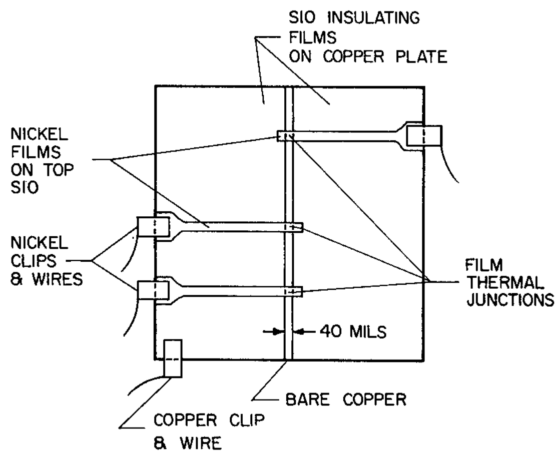


FIGURE 27.—General configuration of surface thermocouples currently being used for heat transfer studies at Ames Research Center.

Research Center, a current program is described in which Cu/Ni thermocouples are created on the surface of a copper plate for heat-transfer studies. The general configuration of the thermocouple is shown in figure 27. Although this figure shows the thermocouples being prepared on a flat sheet, they can be produced on curved surfaces as well. Initially the copper plate is coated by a thin, electrically insulating layer of SiO, deposited by vacuum evaporation techniques, except for a strip approximately 40 mils wide at the appropriate location. A nickel film, about 4 μin. (0.1 micron) thick and 40 mils wide, is then deposited by vacuum evaporation at right angles to the bare copper strip to form a 40-mil square of the nickel and copper. The interface of the two metals in this area is the thermal junction. For virtually all real-time experiments, the thermal junction is at the exposed surface of the copper. The SiO layer is so thin that its thermal insulating effect does not affect heat transfer by gaseous conduction and convection to or from the copper plate. The emittances of the SiO and nickel surfaces are different from that of the copper surface; thus, an overcoating of some material is necessary if heat transfer by radiation becomes an important factor in an application. Before use, nickel wires are clamped to the nickel films for the negative conductors; copper wires are soldered or otherwise attached to the copper plate for the positive conductors. In this arrangement, the film conductors provide practically no disturbances to heat transfer.

Special surface thermocouples have been prepared in this same manner at Ames Research Center in at least one other combination—gold films on nickel plates. To date, only pure metals have been used as evaporated metal films because of the difficulty of evaporating thermoelectric alloys and obtaining the same thermoelectric properties as the solid forms.

Transient surface-temperature measurements are required for the analysis of heat transfer to aerodynamic models in supersonic flow. The change of surface temperature with respect to time at a particular point on the model is a function of the rate of heat transfer to the surface from the high-velocity gases. In any analysis of an aerodynamic model such as a spacecraft model, the heat transfer to surfaces may be desired at a wide variety of locations. Therefore, surface temperatures at many locations may be required. A reliable thermocouple technique has been developed (ref. 49) at Langley Research Center, by which measurements can be made at numerous locations in a model as indicated in figure 28. This technique is based on the premise that all data are obtained within 0.1 sec, a time-length typical of model testing in hotshot wind tunnels. The thermocouples are fabricated from 1-mil Chromel and Alumel wires that are spot-welded to the internal surface of the skin of the model. This skin is only 2 mils thick and is supported

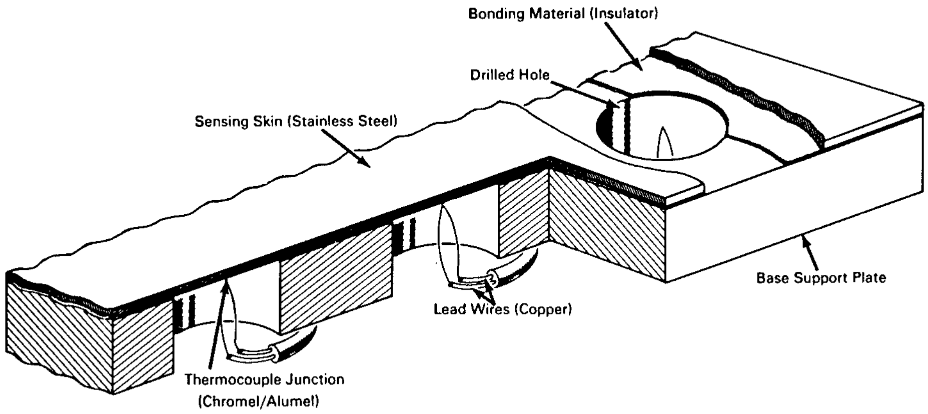


FIGURE 28.—Special thermocouple installation technique for measuring surface temperatures of aerodynamic models at Langley Research Center.

by the relatively thick base plate of the model. At each desired location, the base plate is drilled with a ¼-in. hole; the skin covers the hole and the thermocouple is welded to skin at the center of the hole. In the brief time of the test, the heat lost internally from this surface is negligible; hence, the measured temperatures are those of the skin (302 stainless steel). The skin has a finite mass and acts as a calorimeter by virtue of its specific heat.

This technique is used for extremely short periods of time in a test. Furthermore, only a temperature change of about 2° to 3° F occurs in a test. Therefore, the reference junction for the fine wires can be within a short distance (normally about ½ in.) of the thermal junction. The 1-mil Chromel and Alumel wires are soldered to considerably larger copper wires at the reference junction, and these copper wires conduct the thermal emf signals to the recording instruments. If this technique is used for temperature measurements over longer periods, the reference junction should be at a controlled temperature. For convenience in handling, larger Chromel and Alumel wires could be used from the 1-mil wires to the reference junction.

An analytical study of the time-temperature characteristics of a thermocouple attached to a thin skin of a heat transfer body was initiated at the Engineering Experiment Station at the University of North Dakota under a NASA research grant (ref. 50). The objective was the development of a set of equations by which the effects of thermocouple wire size, thermal properties, and geometric arrangement could be predicted in a variety of heat-transfer mechanisms.

Steady-State Temperature Measurements

Special thermocouples have been developed at several NASA centers for measuring the steady-state surface temperature of an equipment component. The configuration of the thermocouple may be one of several types. Application requirements may demand that the thermocouple have a minimum of disturbance to the flow of heat. As suggested, evaporated-metal film thermocouples can be used in such instances. In other applications, the disturbances to heat flow must be tolerated as a compromise to more stringent requirements of minimum disturbances to the metallurgical structure of the metal or material being instrumented.

An example of evaporated-metal film thermocouples used for steady-state surface-temperature measurements is the work done in the Spacecraft Technology Division at Goddard Space Flight Center. The use of fine-wire thermocouples to measure surface temperatures of thin materials (less than 10-mil thickness), particularly with low emittance surface coatings, can result in large errors because of the difficulty in obtaining surface contact with the thermal junction and the disturbance to the heat-flow paths and the surface properties. A solution to the problem was obtained by a Cu/Ni film thermocouple deposited onto the surface. A thin copper film, about 10 μin. thick, was deposited by vacuum evaporation with a 0.5-in. diameter pattern at the center and a 0.1-in.-wide strip extending to the upper right corner of the pattern (fig. 29). The nickel film was similarly deposited so that its 0.5-in. diameter pattern covered directly the 0.5-in. diameter copper film; the 0.1-in.-wide strip of nickel film extended to the upper left. These strips of copper and nickel films are the electrical conductors from the thermal junction, which is the interface of the overlapping metal films, to the wire connections at the specimen corners. Copper and nickel wires were cemented to the ends of the respective film conductors to complete the connections to the thermal emf-measuring instruments. The plastic sheet specimen shown in figure 29 has the Cu/Ni film thermocouple on one side and an evaporated-film resistance heating element on the opposite side. Calibration data were collected from five of these thermocouples; three were deposited on glass slides and two on the plastic sheet. The results of these calibrations are compared in figure 30 to the thermal emf of the copper and nickel wires used with the film thermocouples. The thermal emf's of all film thermocouples are in very good

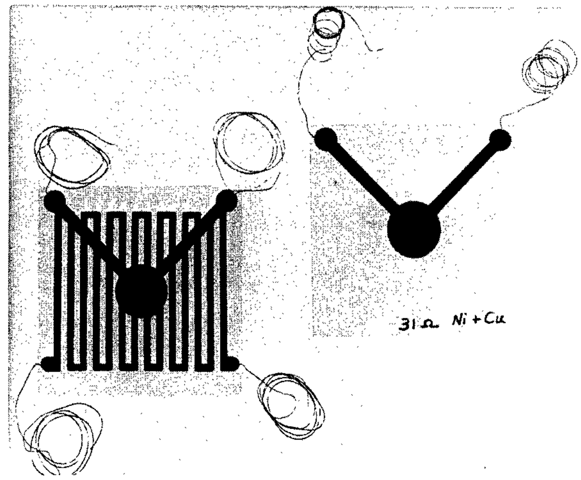


FIGURE 29.—Vacuum deposited Cu/Ni film thermocouples on plastic sheet used in heat transfer studies at Goddard Space Flight Center.

agreement with each other and those of the wire thermocouple (ref. 51).

Special surface thermocouples are being used in a liquid-metal heat-transfer system at the Jet Propulsion Laboratory. Columbium tubing, bent into a helical coil as shown in figure 31, is an electrical heater through which the liquid metal is pumped and heated. Enclosed by insulation, the assembly operates at temperatures above 2000° F in a protective atmosphere. The temperatures of the individual turns of the

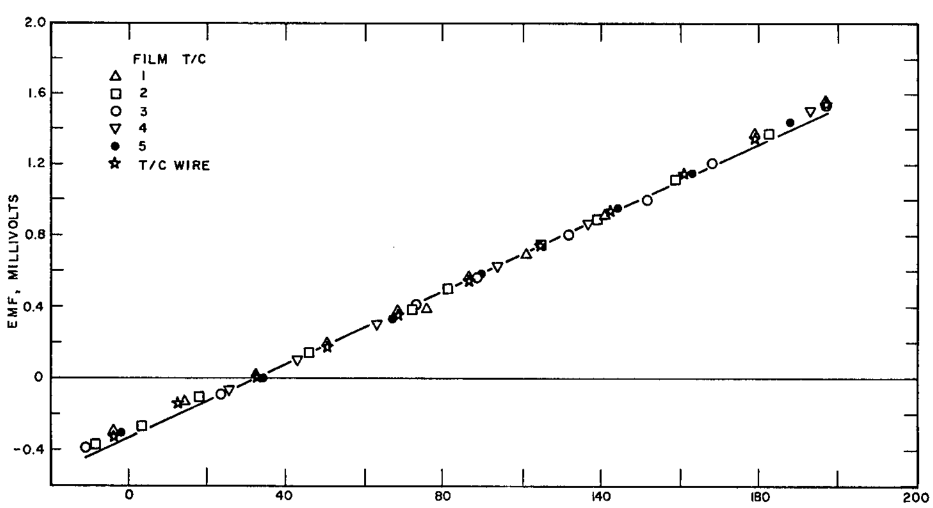


FIGURE 30.—Calibration data for five film and one wire copper/nickel thermocouples.

helical coil must be measured, and thermocouples are the most practical means for the measurements. The reactive nature of columbium at the operating temperatures with most metals other than refractory metals limited the selection of the thermoelements to the tungsten and rhenium alloys; W–5Re/W–26Re thermocouples are used.

The special nature of this thermocouple application is the manner by which the thermocouples are attached. The columbium tubing has a thin wall that prevents drilling a hole into the wall and embedding the thermocouple wires in the wall. Normal procedures would suggest spot-welding the wires to the tubing surface; however, a spot-welded joint changes the crystalline structure of the columbium tubing in a small zone in the vicinity of the weld. This affected zone is sensitive to corrosion at operating temperatures and pressures; therefore, it is a possible location for tube failure and cannot be tolerated. Hence, the wires are mechanically held in place (fig. 32) by a layer of plasma-sprayed tantalum (compatible with columbium in this application). The steps in attaching the wires to the tubing are as follows:

(1) A layer of tantalum about 5 mils thick is sprayed onto the columbium tubing to provide a key for the subsequent layers.

(2) A layer of aluminum oxide about 10 mils thick is plasma-sprayed over the entire area, except on an area of approximately ½-in. diameter where the thermal junction is to be attached to the tubing.

(3) The two thermoelements are laid along the length of the tubing with their ends just beyond the edge of the ½-in.-diameter area; the wires are held there with stainless-steel wire which is removed after the instrumented columbium coil has been installed in the heat transfer loop.

(4) A copper mask, 10 mils thick, with ½-in. hole is laid over the thermoelements and the ½-in.-diameter area free of aluminum oxide; a thick layer of tantalum is plasma-sprayed over the wires to hold them to the original ½-in.-diameter area of sprayed tantalum.

(5) A final layer of aluminum oxide is sprayed over the junction to provide electrical insulation for the thermal junction.

This installation procedure has proved very satisfactory. Between 80 and 100 thermal junctions have been installed on columbium tubing; the mechanical bonds have had adequate strength for the required testing.

IMPORTANT FACTORS IN THE SELECTION OF SURFACE THERMOCOUPLES

The selection of a particular thermocouple for measuring surface temperatures depends primarily upon the reason for making the measurements. Considerably more attention to thermocouple design is necessary for measurements being made to obtain data for heat-transfer analysis than for the measurements made to obtain only the temperature of a specific item. Also, consideration must be given

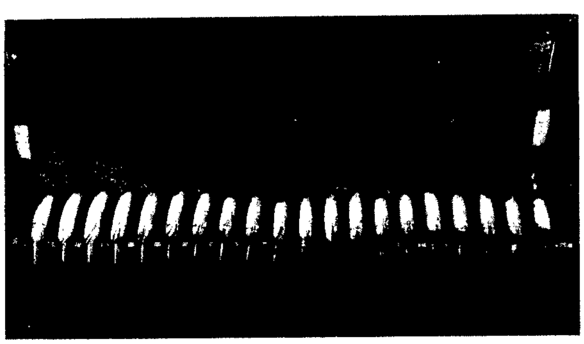


FIGURE 31.—Columbium tubing instrumented with special thermocouples for use in NASA liquid metal heat transfer system.

FIGURE 32.—Close-up view of special thermocouple installation on columbium tubing.

to the other factors common to all applications, i.e., temperature limitations, material compatibility, stability, environment, and instrumentation.

Surface Thermocouples for Heat-Transfer Data

When surface temperatures are being measured for heat-transfer analysis, the thermal junction must be in a plane perpendicular to the heat flow and virtually at the exposed surface. Furthermore, the thermocouple must not appreciably disturb the heat flow to the surface from the hot gases (the major concern at GSFC is surface radiation transfer in vacuum) and from the surface internally to the rear side of the wall.

Designs of film thermocouples used at Ames Research Center and Goddard Space Flight Center are based on these requirements. The film thermocouples are particularly suited for collecting heat-transfer data (figs. 27 and 29). If surface radiative heat transfer is of major concern, the outer surface of the temperature sensor should be coated with a film having the required surface properties. An intermediate electrically insulating coating is required if the outer layer is electrically conductive. One of the difficulties that must be overcome before a metal film thermocouple can be used is the problem of electrical contact between the wire and the film thermoelements. At Ames a strip of foil with a wire soldered to it was clamped against the evaporated film to provide a satisfactory contact. At Goddard the best results were obtained when the wire was cemented into the plastic sheet and the film thermoelement was evaporated over it for the contact. If neither method can be used on a surface, other methods must be devised. A review of various surface thermocouple designs (ref. 52) suggests ways of designing probes that can be inserted in the wall of the apparatus with the thermal junction at the surface.

When thermocouple wires are welded directly to the exposed surface, the thermal junction is, in fact, at the interface of the attached thermocouple wires and the surface. Hence, the wires disturb the heat transfer to the surface, and considerable error can occur in the surface temperature measurements. The magnitude of the errors depends entirely on the type and amount of heat being transferred to the surface. For example, when the surface with the thermocouple wires welded to it is exposed to high-velocity hot gases, the protruding wires will be heated to a higher temperature than the surface of a test model. Heat will then be conducted down the wires and into the metal wall beneath the exposed surface. The conduction of heat through the wires results in a higher local temperature at the thermal junction than at another position on the surface and, hence, causes an error in the temperature measurements. If the surface is exposed to intense radiative heat, the wires will also heat up, but they will mask the surface at the thermal junction. Thus, a more complex effect is created and the thermal junction will again be sensing an inaccurate temperature. If the surface is insulated to reduce the heat flow to or from it, the heat flow along the wires welded to the surface will be virtually zero. In this case, the thermal junction will exist at practically the same temperature as the undisturbed surface; hence, the measured temperature will be reasonably accurate. Experimental studies determining the relative magnitudes of these errors are described in references 53 and 54.

Surface Thermocouples to Indicate Temperatures of a Specific Item

As we have seen, surface thermocouples can give reasonably accurate measurements when the thermocouple and the surface are insulated. Under this condition, the wall temperature is the same as that measured by the surface thermocouple. Thus, the simple technique of attaching thermocouple wires to a surface is practical to measure the temperature of a wall beneath the surface. In this manner, the wall temperatures of the columbium tubing was determined in the liquid-metal heat transfer system at the Jet Propulsion Laboratory with the surface thermocouples shown in figures 31 and 32.

POTENTIAL INDUSTRIAL APPLICATIONS

The potential industrial applications of the

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surface thermocouples are primarily in research studies. This limitation is particularly true for the surface thermocouples used in heat-transfer studies where sophisticated instrumentation and analysis are necessary. There is no limitation in the case of surface thermocouples that are thermally insulated to minimize heat transfer when they are attached to the wall of a tube or an apparatus. Determining bulk temperatures by surface-temperature measurements is common practice in all industries. However, the technique used by JPL to hold the thermocouple wires to a tube (see fig. 32) is an innovation that is practical for temperature measurements of metals which cannot be metallurgically disturbed. Temperature measurements of exotic metal tubing in high-temperature chemical processes can be a direct transfer of this technique.

The thin-film thermocouples such as those developed by Ames Research Center and Goddard Space Flight Center can have considerable value in special applications in industrial and research laboratories. Their fast response, very small mass and volume, and capability of being deposited on unusual surface configurations enable them to be used where conventional wire thermocouples could create considerable errors or interfere with normal heat flow.

CHAPTER 6

Thermocouples for Temperature Measurements of Solids

Thermocouples are widely used to measure temperatures of solids because they are relatively accurate, easy to install, and measure temperatures at particular locations. Because of their simplicity, they often are used in applications where they create disturbances to heat flow; as a result, they generate their own errors in the temperature measurement. When the wires of the thermocouple are very small (e.g., 5 mils), the disturbance is slight. As in the case of surface thermocouples, the effect of the thermocouple is dependent on the magnitude of the temperature gradients (the heat-transfer rate) in the solid. Also, the thermal conductivities of the thermocouple wires and the solid play a role in the thermal disturbances and the resulting inaccuracies. An extreme example is the case where a large Cu/Con thermocouple is loosely held in a hole of an insulating brick; the thermal conductivities of the metals are at least 1000 times greater than that of the brick. The heat flow through the thermocouple wires would be three orders of magnitude larger than that through an equal cross-sectional area of the insulation. The poor fit between the thermal junction and the brick would cause a temperature difference between the junction and the solid; hence, a large error could exist in the temperature measurements. However, if the copper and constantan wires and the brick were perfectly insulated, no heat flow would occur through the wires near the thermal junction and the temperature measurements would be accurate.

Techniques used on NASA programs to eliminate such errors are described in the following section. Guides for using thermocouples to measure the temperatures of solids are also listed.

NASA THERMOCOUPLE DEVELOPMENTS

NASA engineers and scientists use special thermocouples and methods to measure temperatures in unusual situations. This section describes some of the methods used at the NASA centers to minimize heat conduction through the wires; thermocouples are described here, also, to show how they minimize the thermal disturbances to heat flow.

Thermocouples for Determining Temperature Distribution in Ablative Materials

NASA is interested in ablative materials for spacecraft heat shields and rocket nozzles. Evaluation of these materials requires measuring the temperature distributions within the material during exposure to very high heat rates. Since the thermal conductivity of the specimen in these applications is very much lower than that of the wires, thermocouples in the specimens create considerably greater disturbances than similar thermocouples do in normal applications. Because of the extreme conditions of these tests, slight differences in the thermocouple design have significant effects on the thermocouple signals.

At Langley Research Center specimens of ablative materials with various thermocouple configurations were exposed to gases at approximately 6400° F (static temperature) from a 2500-kilowatt arc jet to determine the errors from heat conduction along the wires. Results from these studies (ref. 55) were used to produce an optimum thermocouple design for this type of application; the results are reviewed in this survey. Five thermocouple configurations, mounted in charring ablative specimens and in porous ceramic specimens, were exposed to the hot gases. The designs of the thermocouples are

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shown in figure 33, and their installation in the ablative specimen is shown in figure 34. Type *S* (Pt–13Rh/Pt) thermocouples were used in the ablative specimens and type *K* (Ch/Al) thermocouples in the ceramic specimens. Sensors 1 through 3 had their thermal junctions and a length of each wire, a minimum of 25-wire diameters, across the end of a plug of the same material as the specimen. Comparisons between sensors 2 and 3 and between 4 and 5 were made to explore the possibility of errors in the thermocouple signal from an interaction between resin-glass insulation on the wires and the ablative materials.

The records from the thermocouples in the ablative specimens during exposure are shown in figure 35. The signals of sensors 1 through 3 were identical, but those from sensors 4 and 5 were significantly lower. Results indicate that heat conduction from the thermal junctions of sensors 4 and 5 caused errors as great as 1200° F in these tests. No error was traceable to the interaction of the ablative specimen and the resin-glass insulation. The signals from sensor 4 were the lowest; this effect was attributed to the higher thermal conductivity of the alumina ceramic insulator compared to that of the resin-glass insulator.

The designs of the three thermocouples mounted in the ceramic specimens and the details of the specimens are given in figure 36. Records from tests with the thermocouples

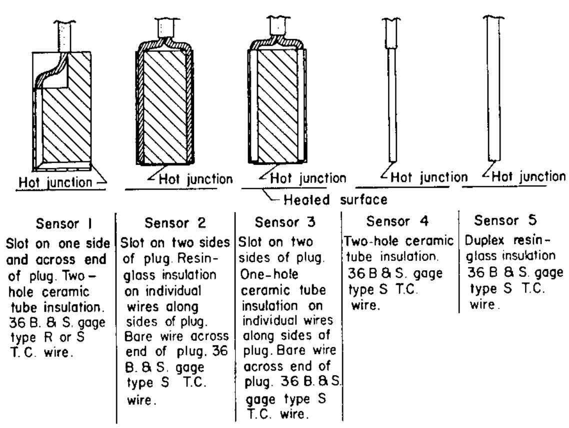


FIGURE 33.—Thermocouple configurations tested in ablative specimens to determine errors from heat conduction along the wires.

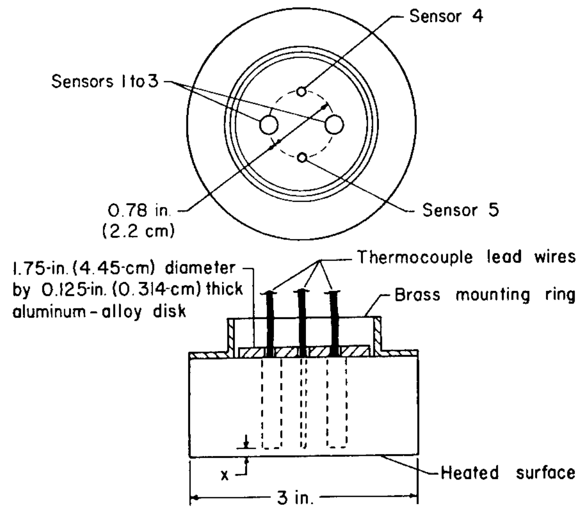


FIGURE 34.—Details of ablative specimen used to evaluate sensors 1 through 5 when exposed for 25 to 95 sec to 6400° F gas from a 2500-kW arc jet at Langley Research Center.

mounted in specimens *F* and *G* are presented in figure 37. In specimen *F*, the plane of the thermal junctions was 3/16-in. from the exposed surface; in specimen *G*, the plane was 1/2-in. The results from these tests agreed with the results obtained from the ablative specimens. The sensors with a length of wire of at least 25-wire diameters in the plane of the thermal junctions gave consistently more accurate temperatures. The heat rates at the thermal junctions of specimen *F* were higher than at the junctions of specimen *G*; the results show greater errors in specimen *F* than in specimen *G*. These tests show that the heat conduction error is a function of heat rate.

A follow-on program at Langley was conducted to determine the effect of the thermocouple wire size and configuration on the internal temperature measurements in the charring specimens (ref. 56). Wire diameters ranged from 1.2 mils to 20 mils; probe configurations were similar to sensors 1, 3, and 4 of figure 33. The results agreed with data obtained during the previous program (ref. 55); in addition, the results showed that errors as great as 1450° F would exist when the 20-mil thermocouples (sensor 4 configuration) were exposed to high heating rates. The thermocouples in the sensor 1 and 3 configurations were susceptible to breakage, which is believed to be caused by differences in thermal expansion between the wires and plug material.

Conditions in these experiments were much more severe than in the normal applications of industry. Therefore, the magnitude of errors in industrial applications would normally be at least one order less, possibly two orders less. Nevertheless, it is obvious that, whenever possible, thermocouple probes should be designed to have a length of thermocouple wires of at least 25-wire diameters in the isothermal plane of the thermal junction. When plug-type sensors are used, the plug materials should be the same as the materials of the apparatus being studied.

As a consequence of the experiments at Langley, other probes have been fabricated in ablative specimens with the thermocouple configuration of sensor 3. These probes are produced with the thermocouples prefabricated in the probe base (fig. 38). Five pairs of 10-mil thermocouple wires are cemented in and positioned by 31-mil ceramic single-hole insulators at 250-mil increments in elevations. The length of each wire in the horizontal direction (the isothermal plane) is about 15-wire diameters. The ablative material is cast in place around the thermocouples and then machined into a cylinder, as suggested by the dashed lines in figure 38. The cylinder is inserted into a larger ablative specimen for the arc jet tests described in reference 55. This thermocouple probe with the five thermal junctions at precise depths from the exposed surface serves as a gauge to measure the erosion or burning rate of the ablative material.

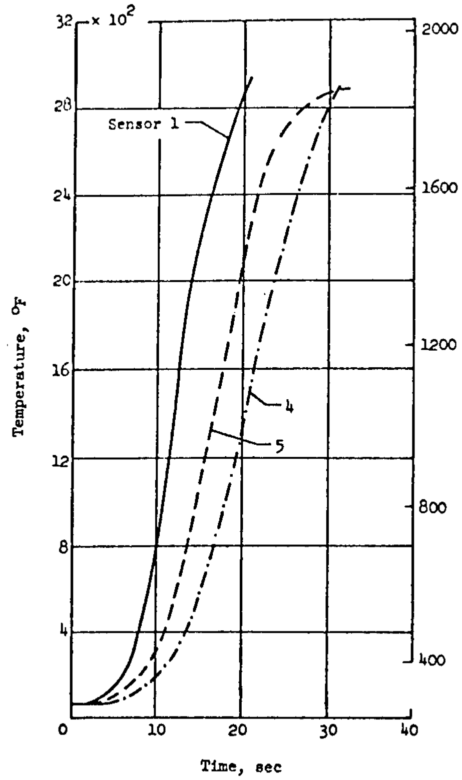
Another NASA contribution to the state of the art is a "consumable" thermocouple developed at North American Aviation, Inc., for MSC (ref. 57) to measure the temperature distribution in ablative materials. The thermocouple is consumable in the sense that it continues to generate temperature signals even though its original thermal junction is melted away by hot gases; conventional thermocouples with the same thermoelements fail and do not recover when the thermal junction is melted. The consumable thermocouple is initially procured as a 40-mil diameter commercial unit with 5-mil W–5Re and W–26Re thermoelements, BeO insulation, and a tantalum sheath.

Two modifications to the commercial unit are significant. One is a 2-mil-thick ceramic coating applied to the tantalum sheath for high temperature protection. The coating consists of a variety of materials that melt at high temperatures and provides a protective layer against oxidation. These thermocouples have been exposed to temperatures above the melting point of the W–26Re thermoelement (5650° F) and have maintained their electrical continuity. If the protective layer had not been effective, the thermoelements would have been oxidized and the electrical continuity would have been broken. Thus, the coating enables the thermocouple to be "self-healing" as hot gases melt and erode the thermoelements during a test.

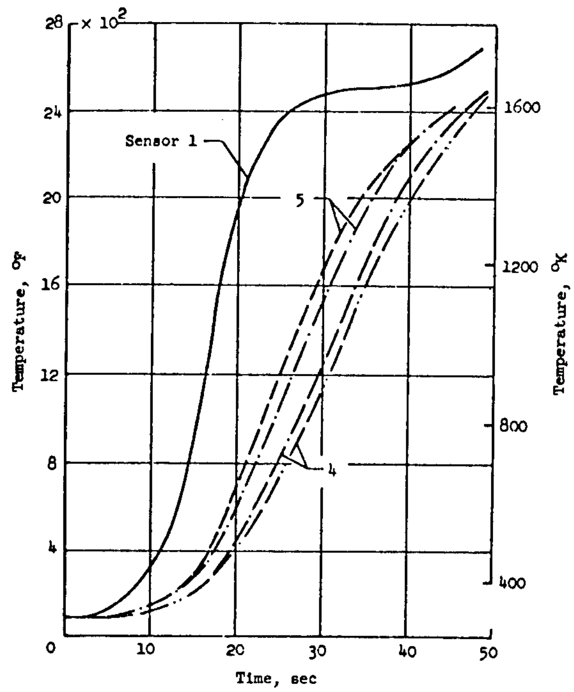
The second modification is a reduction of the tantalum sheath diameter to improve the time response of the thermocouple and to reduce the heat conduction along the sheath from the thermal junction. This reduction is achieved when the 40-mil sheath is chemically milled to a diameter of 32 mils before the 2-mil ceramic coating is applied. A sectioned view of the coated thermocouple assembly is shown in figure 39a.

Consumable thermocouples have been installed in the ablative nozzle materials of large rocket motors. The thermocouples are first mounted in plugs of this material which are then installed in the nozzle (fig. 39b). To reduce errors from heat conduction down the sheath and thermoelements, the first ⅜-in. length of the thermocouple is bent and installed parallel to the exposed surface in the isothermal plane of the thermal junction.

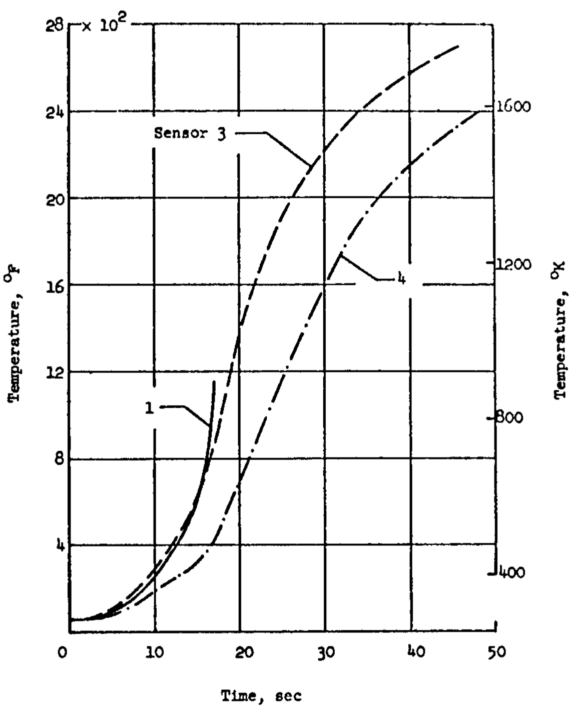
The condition of one of the rocket nozzles after firing is depicted in figure 40. (Positions of two thermocouple plugs are circled in the photograph.) During static motor firing, the surfaces of the plugs were photographed with a high-speed movie camera. When the thermal junction melted (confirmed by photographs), the thermocouple signal was 42.5 mV; the calibration curve, extrapolated to 5650° F, gives 40 mV. Hence, the consumable thermocouple can yield reasonably accurate data. Stability tests



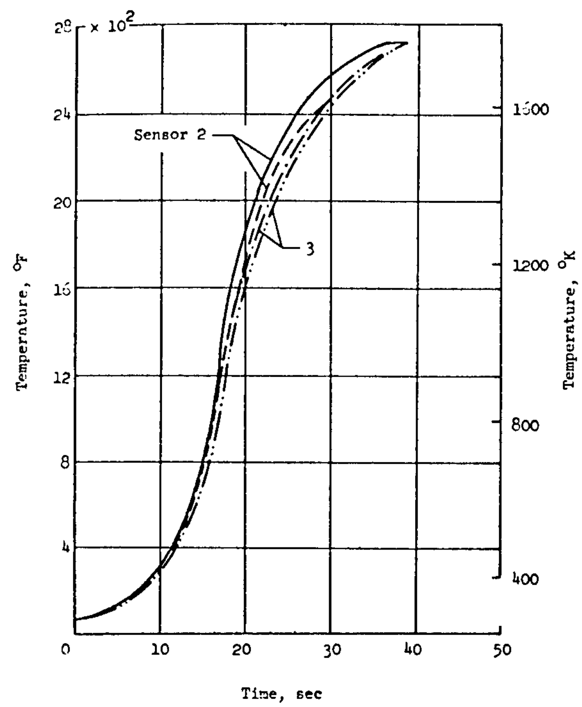
(a) Specimen A.



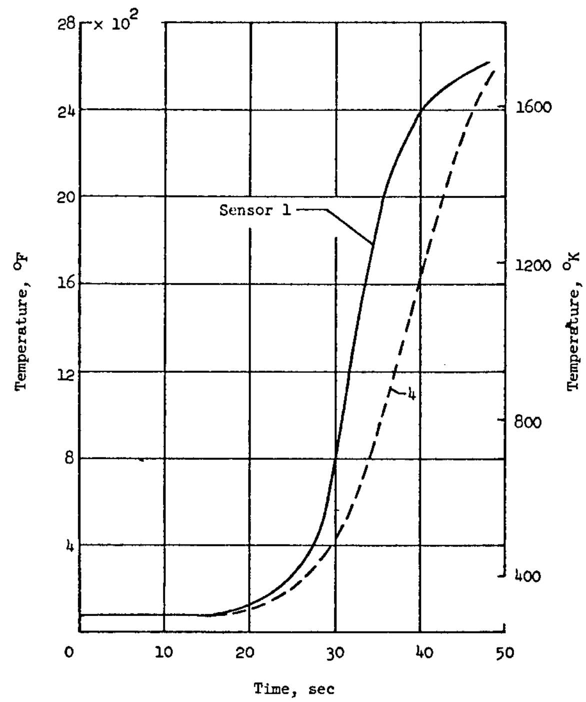
(b) Specimen B.



(c) Specimen C.



(d) Specimen D.



(e) Specimen E.

FIGURE 35.—Temperature-time records of the various thermocouples mounted in five ablative specimens exposed to 6400° F gases.

have not been attempted because the only use of the thermocouple has been for temperature measurements of ablative materials.

Thermocouples for Determining Temperature Distribution in Metals

A different approach was followed in the development of thermocouple plugs to determine the total heat transfer to the heat shield of Project Fire. This was a NASA project to gather inflight data during reentry at velocities slightly higher than return velocities from a lunar mission (ref. 58). In these plugs it was impractical to bend the wires so that they would be in the isothermal plane of the thermal junction. Therefore, the heat conduction errors were minimized by using very small wires (1 mil) and by producing maximum thermal contact of the thermal junctions with the thermocouple plug. The thermocouple plugs in part of the heat shield (the forebody of the reentry package) were beryllium; the others in the heat shield were phenolic-asbestos ablative material. The Republic Aviation Corporation was the prime contractor to Langley Research Center for the design, construction, testing and launch-operation phases of the reentry packages in which the thermocouple plugs were used.

The beryllium plugs were instrumented with the 1-mil thermocouples in the following manner: A core, ⅛ by 13/64 in., was first machined with three grooves along its cylindrical surface. The grooves were 4 mils deep by 4 mils wide and extended along the core the distances from the rear surface—192, 132, and 72 mils. Because of the extremely small dimensions of the core, the rod from which the core was machined was retained as a mandrel to hold the core and to assist in fitting the core into the sleeve of the plug. Ch/Al thermocouples consisting of 1-mil wires were slipped into double-bore quartz insulators, and thermal junction beads were formed by fusion-welding. Each thermocouple with its quartz insulator was cemented into its respective groove. The bead

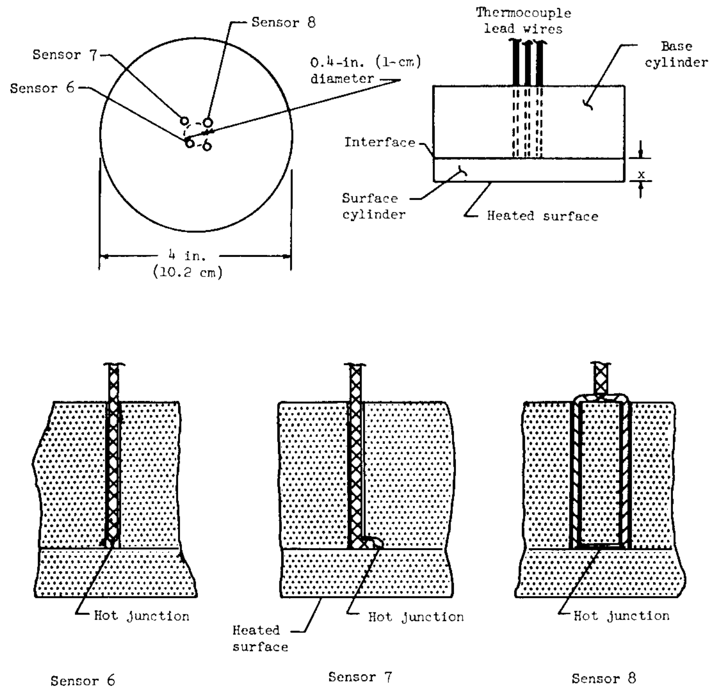


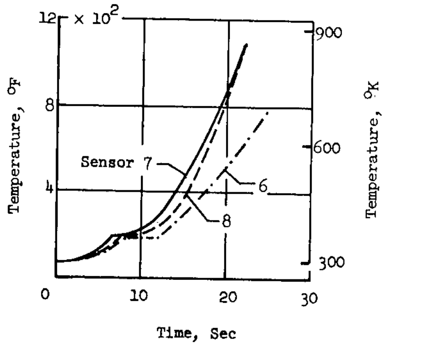
FIGURE 36.—Designs of three thermocouple sensors mounted in a ceramic specimen for determining errors from heat conduction. Sensor 6: Duplex resin-glass insulation. Thirty B & S gage type K T. C. wire. Sensor 7: Duplex resin-glass insulation. Thirty B & S gage type K T. C. wire. Sensor 8: Resin-glass insulation on individual wires along depth of holes in ceramic. Bare wire along interface. Thirty B & S gage type K T. C. wire.

was resistance-welded to the end of the groove and allowed to protrude 0.3 mil above the cylindrical surface of the core so that, after assembly, the inner surface of the sleeve would provide additional force to strengthen the weld of the bead. The exact distance of the center of the bead to the mandrel shoulder was measured with a microscope. The sleeve for the thermocouple plug was $\frac{13}{64}$-in. thick and $\frac{5}{8}$ in. in diameter. For assembly of the core into the sleeve, the core was cooled to −320° F with liquid nitrogen, and the sleeve was heated to between 500° and 600° F. The core was then inserted into the sleeve to create a shrink fit; the assembly is shown in figure 41.

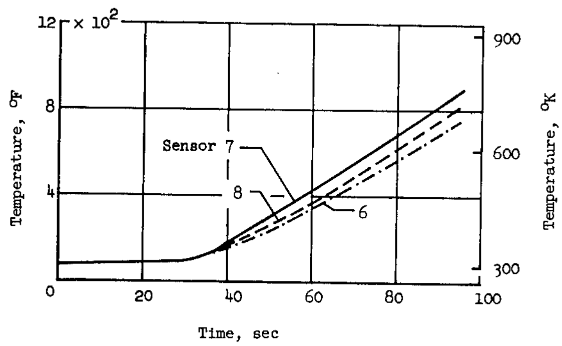
The thermocouple plugs were next installed in the beryllium heat shield of the reentry package with another shrink fit; the surface of the sleeve of the plug was made flush with the adjacent surface of the heat shield. The mandrel was machined away before the end of the core of the thermocouple plug was hand-finished to be flush with the surface of the sleeve. Because of the care and precision with which these miniature thermocouple plugs were installed, the precise location of each thermocouple bead was known to within ±2 mils after final installation.

Thermocouple plugs also were installed in the phenolic-asbestos ablator layers of the heat shield. For these plugs, the cores and sleeves were machined from the phenolic-asbestos material, and the 1-mil thermocouples within the quartz insulators were phenolic-bonded in the grooves of the core. The core was slipped into the sleeve and held there by a phenolic bond.

Although the thermocouple installation technique developed on Project Fire requires high precision and the thermocouples are fragile, they yielded the desired heat-transfer data from the in-flight tests. Some failures of thermo-



(a) Specimen F.



(b) Specimen G.

FIGURE 37.—Records of three thermocouple sensors in ceramic specimen when exposed to 6400° F gases.

couples were expected. For example, in Fire II, 144 thermocouples were used with a redundancy factor of 3. Before lift-off, 21 thermocouples were inoperative because of opens or shorts; these were primarily failures of the extension lead wires, not the 1-mil thermocouple wires. During flight about an equal number failed to produce data.

Thermocouples for Measuring Average Temperatures of Metals

Measuring temperatures of a turbine blade is an example of an application of a thermocouple for obtaining the average temperatures of metals. Normally the thermocouple could be attached with ease, but in this application it was not, since the wires had to be embedded in the blade wall having a thickness of only 10 mils (ref. 59). The blades were hollow, air-cooled turbine rotor blades tested in a commercial

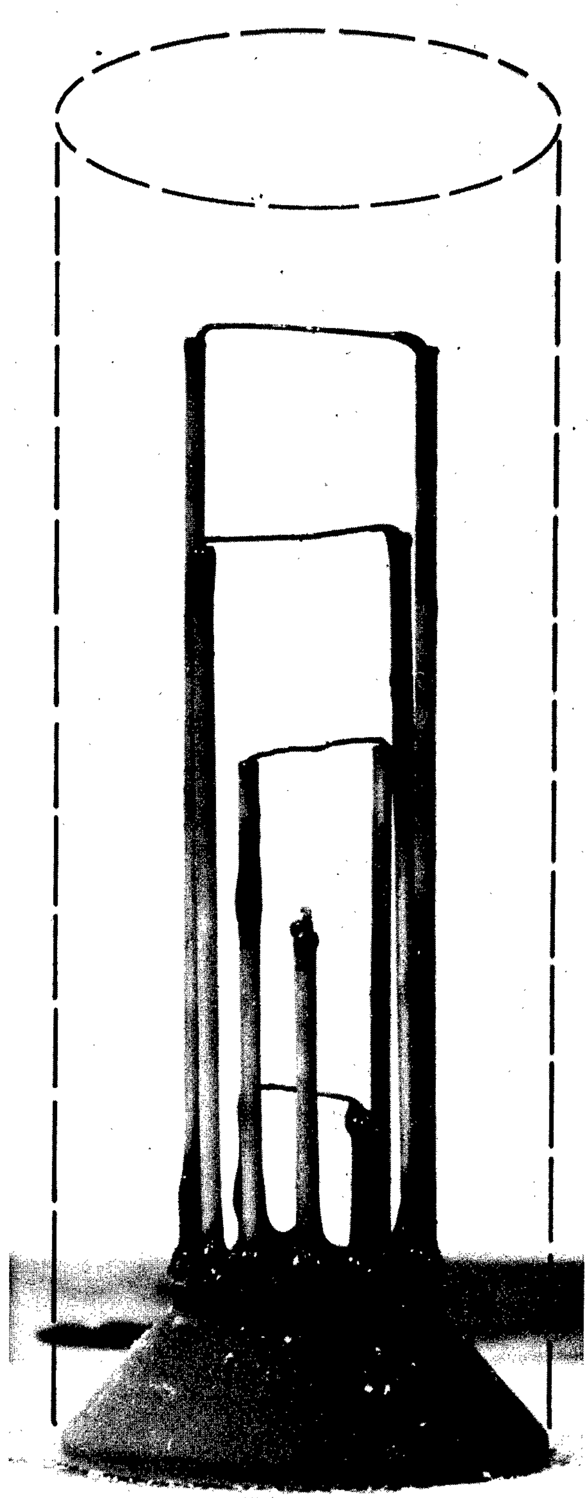


FIGURE 38.—Photograph of prefabricated thermocouples for cast-in-place gauge to measure erosion (burning) rate of ablative test specimens.

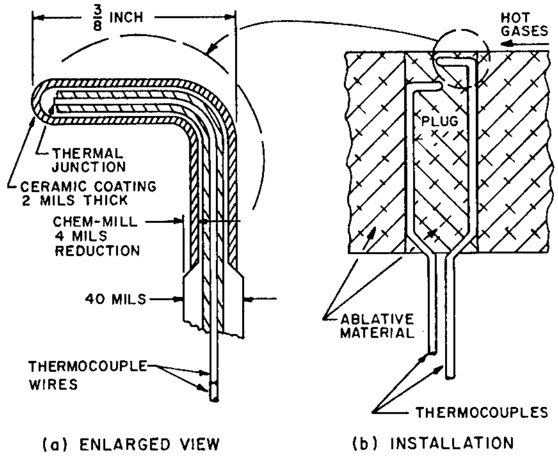


FIGURE 39.—"Consumable" thermocouple, having ceramic coating to provide self-healing action at high temperatures, measures temperatures in ablative materials (ref. 57).

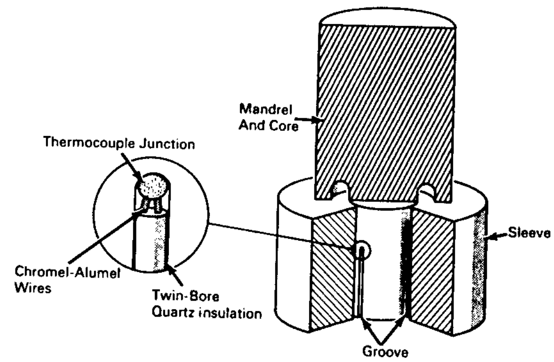


FIGURE 41.—Thermocouple plug with miniature thermocouples installed in core to provide precise locations of thermal junctions.

turbojet engine. The method of installing the thermocouples consisted of cementing the wires in grooves on the rear side of the blade (fig. 42). Since the wires were only 5 mils, extreme care and precision were required to install and cement the wires in the grooves. As indicated in figure 42, a single groove was used for both thermocouple wires; another method also was used which had individual grooves for the wires. In this research program, 55 thermocouples were installed in turbine blades, and 47 satisfactorily operated for times ranging from 2 to 30 hr. In the program, both methods of installing the thermocouples gave satisfactory results; one was not superior to the other. Although there were no clearly defined isotherms at a given time in the blades, the intimate contact of the cemented thermocouple wires with the grooves eliminated heat-conduction errors from the thermal junctions.

The accurate measurement of the temperatures of solids depends on making maximum thermal contact between the thermal junction and the solid. The miniature thermocouple plug used on Project Fire provided this type of contact. Other techniques have been devised at various NASA centers; several of these will now be described.

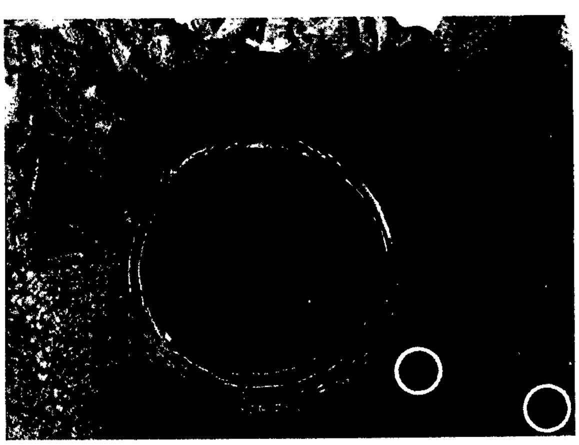


FIGURE 40.—Nozzle of rocket motor after static firing, instrumented with "consumable" thermocouples mounted in plugs which are indicated by the white circles.

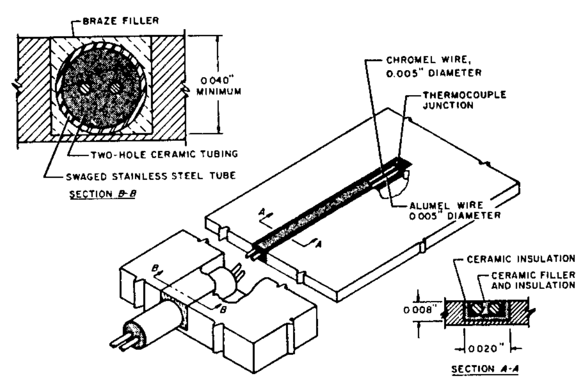


FIGURE 42.—Method of installing a thermocouple in an 8-mil-thick wall of an air-cooled experimental gas-turbine blade. The wires are cemented in a single groove.

Technique No. 1

At North American Aviation, Inc., the turbine nozzle temperatures of the J–2 fuel turbopump were required during operation on a program with MSFC (ref. 60). For accurate nozzle vane temperatures, the thermal junction was located at the midpoint of the vane. A technique was developed for capacitance-welding the end of the thermocouple wires to the bottom of a hole in the vane. As suggested in figure 43, the electrodes from a capacitor welder were attached to the thermocouple wires and the vane. The capacitor was discharged through a small gap between the wires and the bottom of the hole in the nozzle vane. Immediately following the discharge, while the ends of the wires were still molten from the electric arc, the wires were moved to make contact with the bottom of the hole and held there to make the weld. This technique provides an excellent thermal junction and can be used for installing thermocouples in a variety of metals; however, poor results are obtained with aluminum and copper. Because of the high thermal conductivity of these metals, the molten metal solidifies before a weld can be made.

Technique No. 2

Another technique for providing maximum thermal contact of the thermal junction is illustrated in figure 44. When the surface radiative properties of aluminum coatings with Al_2O_3 films were being determined in a study at Goddard Space Flight Center (ref. 61), it was necessary to measure the temperatures of the stainless-steel specimen substrate, which was 1.65-in. diameter and ⅛-in. thick. In opposite edges of the base, No. 2–56 threads were cut. At the bottom of each threaded hole,

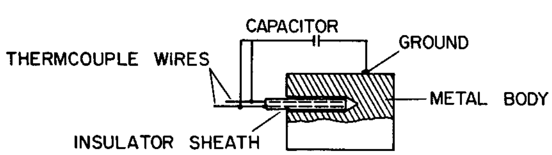


FIGURE 43.—Method of forming a thermal junction at the bottom of a hole in a nozzle vane of a fuel turbopump for temperature measurements of the vane.

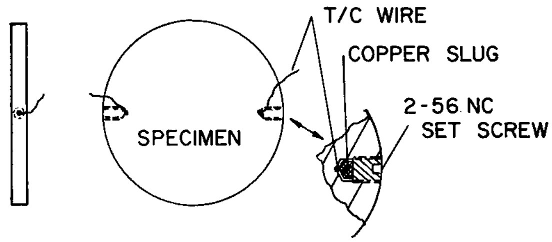


FIGURE 44.—Measurement of the specimen temperatures in an experiment at Goddard Space Flight Center by clamping 3-mil thermocouple wires in opposite edges of specimen base.

a 12-mil hole was drilled from the rear surfaec of substrate. The thermocouple wires, 3-mil copper and constantan, were inserted in the holes and clamped with copper slugs by No. 2–56 set screws; the copper wire was clamped at one edge and the constantan wire at the other. Thus, the mean temperature of the substrate was determined by the thermoelements because the substrate was a part of the thermocouple circuit. The use of the small wires and the excellent thermal contact between the wires and the substrate virtually eliminated heat-conduction errors from the thermocouple signals.

Technique No. 3

A threaded technique (ref. 62) has been used at Langley Research Center for attaching thermocouples to walls of wind tunnels for measuring the wall temperatures. As shown in figure 45, a 40-mil metal-sheath thermocouple was silver-soldered into the shank of a 3–56 screw. The thermocouple wires were extended beyond the end of the screw, bent into a small

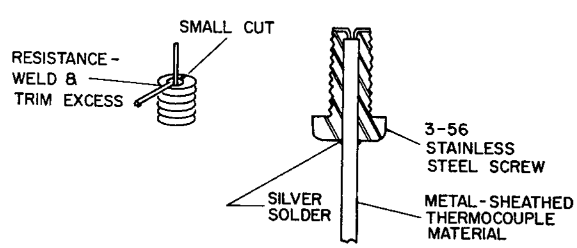


FIGURE 45.—Threaded thermocouple configuration for measuring temperatures of wind tunnel walls at Langley Research Center.

groove with a depth about one-half the wire diameter in the end of the screw, and resistance-welded in the bottom of the groove. The excess wires were removed with a fine file. The thermocouple was then installed in a threaded hole of the wall. The thermal junction was slightly deformed when the screw was tightened to force the junction against the bottom of the hole. Hence, excellent thermal contact was assured. When the wall temperatures were considerably above ambient temperatures, the metal sheath of the thermocouple was wrapped with insulation to decrease the heat conduction along the sheath.

GUIDES FOR DESIGNING THERMOCOUPLES FOR TEMPERATURE MEASUREMENT OF SOLIDS

As emphasized in this chapter, two factors must be considered in designing a thermocouple installation for accurate temperature measurements of solids. These are the heat conduction along the thermocouple wires and the thermal contact between the thermal junction and the object. Both of these factors can introduce errors in the measurements; however, the magnitude of the errors is a function of the heat-transfer rate in the solid. Recommended practices for minimizing the effects of heat conduction along the wires and poor thermal contact are:

(1) Bending the thermocouple wires so that a length of each wire of at least 25 wire diameters is in the isotherm of the thermal junction

(2) Reducing the wire size to a practical minimum

(3) Providing intimate contact of the wires with the solid by thermally conducting cement

(4) Selecting thermoelements with low thermal conductivity

(5) Bonding or resistance-welding the thermal junction to the object

(6) Thermally insulating the thermoelements where they protrude from the object.

In the various NASA thermocouple-development programs described in this chapter, at least one of these recommended practices was followed in the design of each thermocouple.

POTENTIAL INDUSTRIAL APPLICATIONS

The majority of thermocouples in use today are designed for the temperature measurement of solids. In general, NASA-developed techniques for providing maximum thermal contact and thermal response are applicable in nearly all industries using thermocouples. However, in two particular industries, specific developments are suggested as having potential applications.

Steel Industry

The consumable thermocouple discussed in this chapter appears especially applicable, in larger diameter assemblies, to temperature measurements in such places as open hearth roofs and blast furnace walls. It may be useful where the presence of vapors precludes the use of optical pyrometry and where constant erosion of the walls makes use of regular thermocouples impossible. The ceramic protective coating of the consumable thermocouple could possibly eliminate the protective wells used in such applications; hence, this thermocouple would respond more rapidly to temperature changes. Consequently, improved temperature control would result that could either improve the quality of the product or reduce the time needed to produce it. At temperatures above 3500° F, shunting errors of the thermoelements of the consumable thermocouple would be significantly reduced by using the batman insulator configuration discussed in chapter 3.

Turbine Engine Industry

Average temperatures of rotating turbine blades and fixed turbine nozzle blades can be accurately measured by the NASA techniques discussed in this chapter; turbine engine manufacturers can use these techniques for research studies. The thermocouple for measuring the fixed turbine nozzle blade temperature could be installed on engines for routine service of aircraft, trucks, and ships. The increased accuracy and time response of this thermocouple could provide improved controls for smoother running engines, faster response to acceleration, and reduced fuel consumption.

CHAPTER 7

Special Thermocouples Used in Energy-Transfer Gauges

Temperatures of a gas, liquid, or solid are often measured for their use in energy-transfer calculations (primarily heat-transfer). In many applications, the temperatures of hot gases are not as important as is the effect they have on an object in their path. The heat transferred to the object from the gases might cause it to melt or to damage a heat-sensitive component within the object. For example, the ablative heat shield of the Apollo spacecraft is designed to protect the astronauts and their instruments during reentry. In the development of these heat shields, electric arc tunnels were used to evaluate a wide variety of candidate shield materials. Temperatures of the gases are so high that the conventional concept of temperatures is inadequate to describe the state of the ionized gases. The measurement of these temperatures is impossible except by a few very sophisticated techniques. However, thermocouples incorporated into heat-transfer gauges are constantly being used to monitor the heating effect of the hot gases.

Several instruments (commonly called heat-flux gauges), which determine the rate at which heat is being transferred to a gauge, are described in this chapter. The total quantity of heat transferred to a surface is measured by heat-transfer sensors, called calorimeters; the rate of heat transfer is obtained by determining the time-rate of the temperature change of the calorimeters.

The heat-flux gauges and calorimeters are used almost entirely for the measurement of the heat transferred to the surfaces from gases by convection. In wind-tunnel operation, the convective heat-transfer gauges provide data for calculating the amount of heat which is expected to be transferred to a spacecraft or a rocket in actual flight.

In addition to the convective heat-transfer gauges and transducers, several sensors will be described that were developed by NASA programs to detect forms of energy other than convective heat energy. The rate of heat removal by a liquid that cools a particular device is necessary operational data. A heat-rate transducer for liquids and a technique for its calibration will be described. Sensors for measuring only thermal radiation energy have been developed or studied on NASA programs and are included in this section. The development of a unique "intrinsic"* thermocouple is a valuable contribution received from the Rover Program for determining pulse nuclear radiation energy, and a discussion of it will be given in this chapter.

CONVECTIVE HEAT-TRANSFER GAUGES

The gauges for measuring convective heat-transfer rates are chiefly used in wind and arc tunnel studies and in rocket engine and gas turbine research at the NASA centers to determine the transfer of heat from hot gases to the surfaces of models. The two main classes of these gauges are the heat-flux gauge and the calorimeter.

Heat-Flux Gauges

Heat-flux gauges used on NASA programs have been the result of experimental developments of various types of gauges and analytical studies on their theory and operation. Both activities are described below.

*An intrinsic thermocouple may be described as one in which heat is internally generated in its thermal junction—by nuclear-energy exposure, for example.

Experimental Developments

Extensive work in developing heat-transfer probes has been done at Lewis Research Center. Scientists there have developed several different kinds of gauges for studies in high-temperature, high-velocity gases. In each of these, the thermocouples are used for temperature measurements that are first related to the flow of heat and then to the temperature of the gases (ref. 63). The probe developed for measuring the steady-state rate of heat transfer at the stagnation point of a hemispherical cylinder is shown in figure 46. The principle of axial heat conduction through a cylinder of a known thermal conductivity is used for the heat-rate determination. One end of the cylinder is located at the stagnation point of the probe and is heated by the stagnation gases; the other end is exposed to the flow of a coolant in the interior of the probe. The cylinder consists of three cylindrical disks jointed end to end; the "active" disk at the center section is the thermal-conductivity segment, constantan. Brazed to each end of the constantan cylinder is a copper disk that provides a uniform temperature field across the diameter of the cylinder. The thermal junctions for measuring the temperature difference across the constantan cylinder are located at the copper-constantan interfaces. Appropriately insulated copper and constantan wires are peened into holes in the respective segments of the composite cylinder. The heat-transfer rate is calculated by the equation of steady-state, one-dimensional, conductive heat flow through a solid.

Results of three identical probes tested in Mach number ranges of 0.2 to 0.8 and 2.8 to 3.5 established a correlation factor, Q_{th}/Q_m, for the probes of 1.3, with a standard deviation of ± 5 percent. The factor is the ratio of the theoretical heat to that measured by the probe. This relatively high factor is attributed to radial heat losses from the front copper disks to the hemispherical envelope; this assumption was substantiated by subsequent calculations.

A steady-state heat flow rate (flux) gauge designed at Jet Propulsion Laboratory on a NASA program for low heat-transfer rates is shown in figure 47. This gauge operates on the same principle as the previous gauge, except

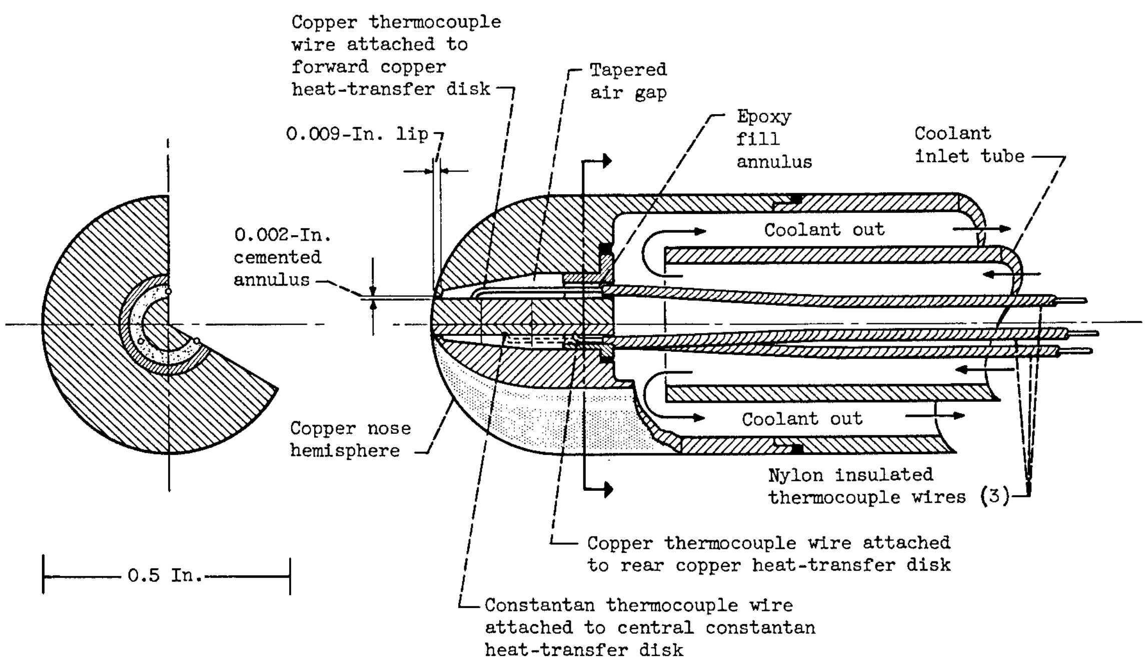


FIGURE 46.—A probe with a Cu/Con/Cu differential thermocouple for measuring stagnation-point, steady-state heat transfer rates of high velocity gases.

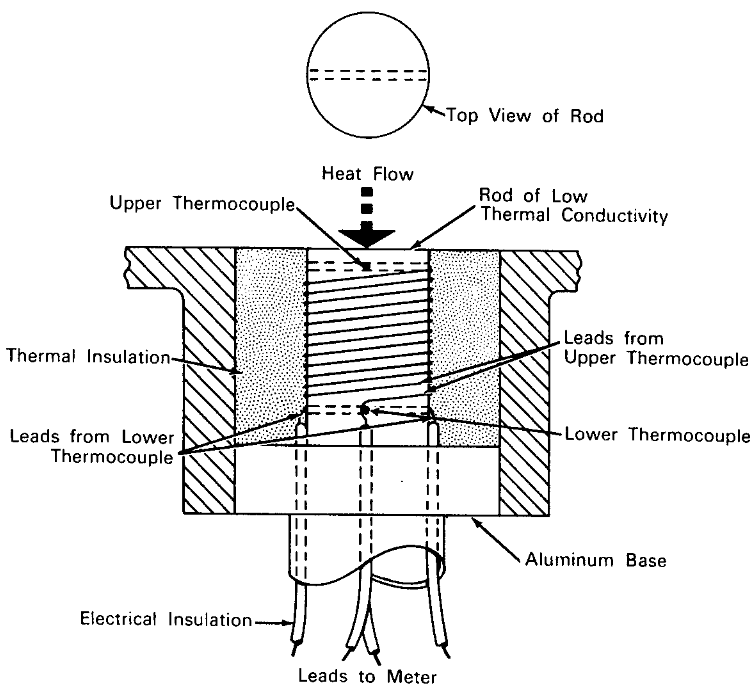


FIGURE 47.—A design of a heat-flux gauge for low rates at steady-state conditions from convective heating.

that the axial heat-conducting cylinder is made of a material with low thermal conductivity, such as polytetrafluoroethylene. The thermal junctions for measuring the temperatures at each end of the cylinder are positioned on the axis of the cylinder by inserting them in tight-fitting, diametrically drilled holes through the cylinder (ref. 64).

The thermal junction must be butt-welded and reduced to the wire diameter to provide a minimum disturbance to the heat flow through the cylinder. The leads from the upper junction must be wrapped around the cylinder many times to provide a very long heat leak path from the hot thermal junction, as the wires have a thermal conductivity at least an order of magnitude higher than that of the cylinder.

For valid operation, the gauge must be operated at steady-state conditions; therefore, heat must be absorbed by a coolant at constant temperatures and flow rates. A major factor in the design of this gauge is the possible heat flow out of the cylinder between the two thermal junctions. When this gauge is used, insulation surrounding the cylinder must have at least two orders of magnitude lower thermal conductivity than that of the cylinder to make this heat flow insignificant. Because of the low thermal conductivity of the cylinder, several minutes are required to achieve equilibrium conditions; hence, this gauge is primarily suited for long-time experiments. The dimensions of the gauge govern the equilibrium time. To ensure reasonable accuracy, all factors must be considered when the dimensions and materials are being specified for this gauge.

A steady-state heat-flux gauge used at Langley Research Center is shown in figure 48. The gauge is used for determining the heat-transfer rates to the combustor liner of the 7-in. Mach 7 facility. The gauge operates on the principle of one-dimensional axial heat flow in a thick-walled hollow cylinder of a metal of known thermal conductivity, i.e., constantan. In this gauge the constantan acts as a common thermoelement in a Ch/Con differential thermocouple. One Chromel wire is brought to the exposed surface through the

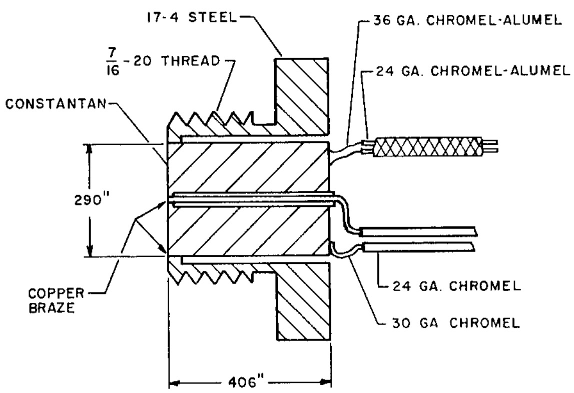


FIGURE 48.—A steady-state heat-flux gauge used in the combustor liner of the 7-in. Mach 7 facility at Langley Research Center. A differential thermocouple provides a signal proportional to heat rate.

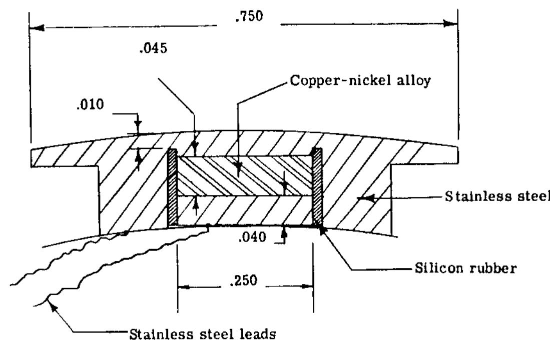


FIGURE 49.—Cross-section details of a differential thermocouple heat-flux gauge used in the Langley 20-in. Mach 6 wind tunnel.

hole in the center of the constantan cylinder. The hot thermal junction is formed by copper brazing the Chromel wire to the surface of the hole in the constantan. The thermal junction is formed essentially at a circular line (the last point of contact between the two thermoelements), approximately 15 mils behind the exposed surface. The cold thermal junction is formed by spot-welding a second Chromel wire to the rear surface of the constantan cylinder. A 5-mil Ch/Al thermocouple is spot-welded to the rear of the cylinder for monitoring the rear surface temperatures of the constantan cylinder. The radial losses from the cylinder to the mounting body are minimized by using a 20-mil air gap between the surfaces of the cylinder and the internal surfaces of the mounting body.

For operation, calibration of the gauge is necessary to determine the differential thermocouple signal for a given heat flow rate. This signal varies with temperature because of the nonlinearity of the Ch/Con differential thermocouple, the nonlinearity of the thermal conductivity of constantan, and, of greater importance, the increase of radial losses with increasing temperatures. The signals from the gauge during transient periods of the combustor operation could be analyzed with a computer, if necessary. The thermal capacitance of the cylinder and the time rate of temperature change of the gauge would have to be considered in this case.

Another steady-state heat-flux gauge used at Langley is shown in cross-section in figure 49. This gauge was designed on the basis of one-dimensional heat flow through a ¼-in.-diameter by 45-mil-thick copper-nickel alloy disk (ref. 34). The front face of the disk was brazed to the stainless-steel gauge cap and the rear face to a stainless-steel disk, 40 mils thick. A stainless-steel wire, welded to the rear surface of the gauge cap, provided the positive thermoelement; a second stainless-steel wire, welded to the rear face of the stainless-steel disk, provided the negative thermoelement. Thus, the heat-flux gauge was a differential thermocouple with the thermal junction at both interfaces of the stainless steel and the alloy. The thermal emf was proportional to the heat flux through the gauge, but the proportionality factor had to be determined by individual calibrations. The edges of the disks were insulated with silicone rubber to reduce losses. In operation, the gauge was press-fitted into the wall of a model.

Analytical Studies

During the early scale-model "hot-flow" testing of Saturn I, the large quantities of accumulated data were difficult to analyze. The problem was lack of previous experience in heat-flux measurements of the magnitudes encountered. As a result, MSFC started a study program to analyze and develop sensors employing the latest state-of-the-art concepts. An authoritative report (ref. 65) was prepared to describe the theory and application of the various heat-flux gauges that were being used for tests continuing for more than 1 sec. Since the steady-state gauge can be used in several types of operation, design parameters for producing these gauges for a particular energy rate and a given signal sensitivity were prepared. The response time was also expressed in terms of the geometry of the gauge. Special considerations were discussed for gauges that had been designed for convective measurements as well as for those designed for combined convective and radiative measurements. As a result of this work, a thorough understanding of heat-transfer gauges using thermocouples can be readily obtained without a rigorous mathematical background.

Calorimeters

Calorimeters are heat-transfer gauges developed on the basis of the heat stored in a given unit of mass of the gauge. Thus, the signal from the thermal junction of the thermocouple is directly related to the quantity of heat absorbed by that unit of mass from the beginning of the test, i.e., the thermal capacity, or the product of the mass and the specific heat of the material. These gauges are usually called slug transducers. In long-duration tests, the heat lost from the calorimeter is accounted for in the calibration curves.

Both experimental and analytical programs have been conducted at the NASA centers, and these will be described below.

Experimental Programs

Several types of calorimeters have been developed; one type represents an advance in the state-of-the-art of the conventional slug calorimeter to permit operation at temperatures to 2500° F. Another type, a rapid-responding calorimeter, is used in wind-tunnel runs of 0.1 sec.

The high-temperature slug calorimeter used a graphite sensing element, representing an improvement over other materials being used because of the stable emittance of graphite. A program was conducted by Southern Research Institute to develop the graphite sensing element for MSFC (ref. 66). The major problem was the attachment of thermocouple to the graphite to prevent a reaction between the graphite and the thermocouple. A successful solution was obtained by vapor-depositing a 2.5-mil tungsten layer on the graphite to serve as a carbon diffusion barrier for the thermocouple. A Pt–10Rh/Pt thermocouple was then flash-welded to the tungsten layer to form the thermal junction. A calibration of a prototype calorimeter (fig. 50) has indicated excellent repeatability in operation to 2300° F.

A calorimeter for operation under transient conditions was developed at Langley Research Center and is shown in capsule form in figure 51. This sensor was designed for test runs of 0.1-sec. duration; consequently, it has a very small mass. A 1-mil Ch/Al thermocouple is welded to the internal surface of a 2-mil thick by ½-in.-diameter stainless-steel disk which is supported at its edge. Because it can be used as an individual sensor mounted in a test model (ref. 67), its presentation in this chapter is warranted. (Multiple installations of this sensor were discussed in the chapter on surface thermocouples.) In brief, the temperature rise of a very small unit mass of the disk is measured. The duration of its exposure to heat is so short that radial heat conduction through the disk and out the wires and convective losses from the rear of the disk are considered negligible. Thus, the temperature of the unit mass at any instant during the test run is proportional to the quantity of heat absorbed by it. Experimental results compare favorably with theoretical results (ref. 49).

The calorimeter sensor at Langley was used successfully in a variety of configurations such as a wedge, a tube, and the leading edge of miniature airfoil (ref. 68). The configuration is limited only by the skill of the technicians who produce the probes and handle the 1-mil wires. To date, Langley experts have been able to fabricate nearly every probe requested.

Analytical Programs

In many studies at NASA centers, the quantity of heat transferred was not needed as much as the rates of heat transfer. The calorim-

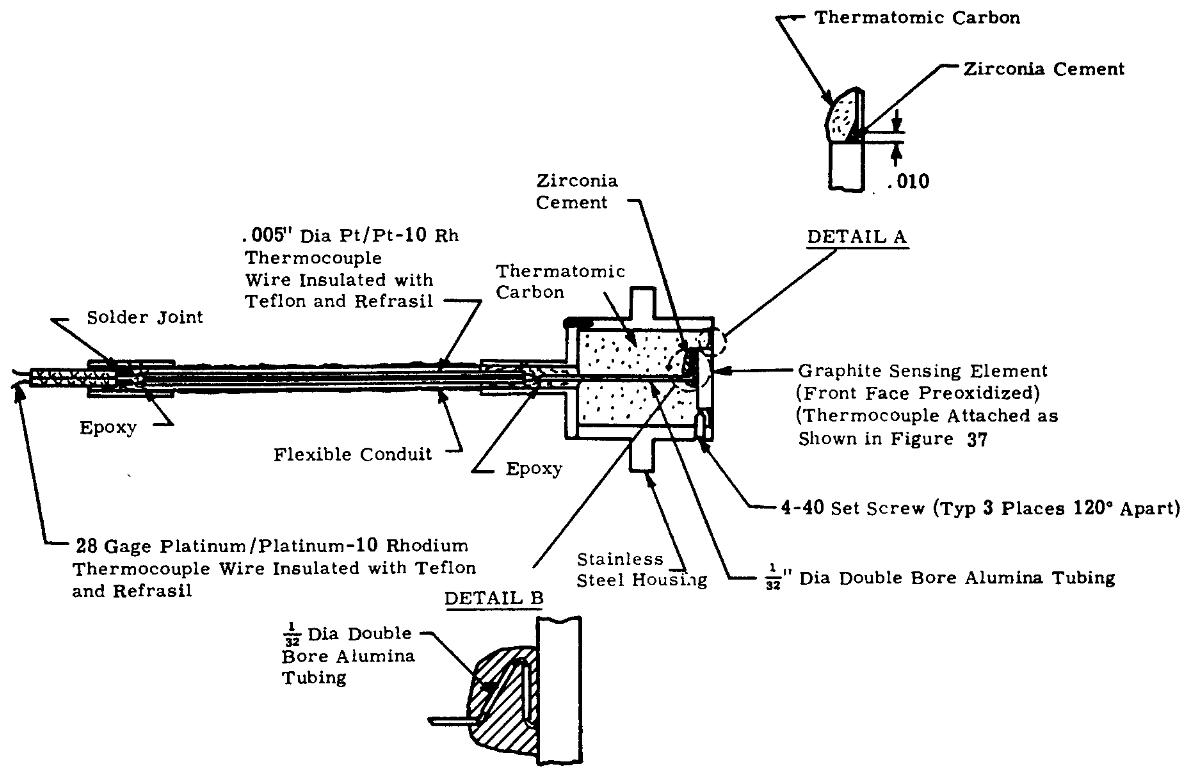


FIGURE 50.—Prototype slug calorimeter with a graphite sensing element which operates with excellent repeatability to 2300° F.

eter could be used for these rates as well as the heat-flux gauges. In the course of the tests, the signals from the calorimeters would be continuously recorded. Thus a heat/time curve was obtained. Because the rate of heat transfer is the slope of this curve at any time, the rate was readily determined. Generally, a simple computer operation would be applied to the data in the data-acquisition system to produce and print out the rate of heat-transfer data.

In previously discussed analytical work sponsored by MSFC (ref. 65), the theory and applications were extended to the slug-type calorimeters (fig. 52). Parametric representations were made for the loss factor, the response time, slug thickness, exposure time, and thermal diffusivity. Thus, the basic principles upon which the calorimeters operated could be clearly understood.

Another analytical study was sponsored by MSFC to determine the temperature deficiency of a calorimeter for long-time testing (ref. 69). Temperature deficiency is the difference between the temperature indicated by the thermocouple in the calorimeter, as seen in figure 52, and the temperature the test surface would have been if the thermocouple had not been there. In one example, the deficiency was calculated to be 8.5° F at 1000° F and was expressed as a linear relation with indicated temperature.

Studies were later sponsored by MSFC to analytically and experimentally investigate effects of the size and the surface temperatures of a slug calorimeter on the accuracy of its measurements when the calorimeter is operated in the hot environment near the exhaust of a rocket engine. Results indicated that errors caused by these factors are serious enough that they must be considered (ref. 70).

OTHER ENERGY SENSORS

As a result of NASA programs, several types of energy-sensing devices have been developed in addition to the convective heat-transfer sensors. These include devices for measuring

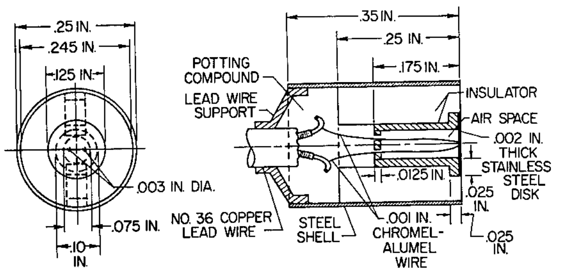


FIGURE 51.—A calorimeter for operation under transient conditions (complete test in less than 0.1 sec) that uses fine-wire thermocouple for temperature measurements (ref. 67).

heat absorbed in cooling water, thermal energy radiated from rocket gases, and nuclear energy radiated in a reactor environment.

Heat-Transfer Transducer for Liquids

A special transducer was developed at Ames Research Center to determine the rate at which heat was being absorbed by cooling water in an arc-plasma generator used in very high-temperature arc tunnels (ref. 71). The transducer is a specially designed thermopile mounted in an electrically shielded housing. Details of the assembly are given in figure 53. There are 10 thermal junctions in the water-

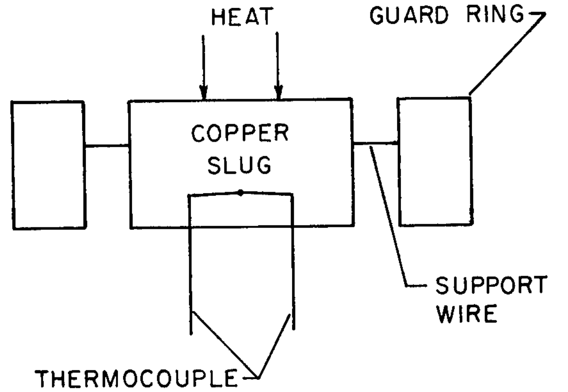


FIGURE 52.—Schematic of slug calorimeter investigated in a NASA parametric study, that uses a small thermocouple to determine the quantity of heat absorbed by the slug.

supply line and a corresponding number in the return line for signal amplification; nominal sensitivity for the thermopile arrangement is approximately 0.22 mV/° F difference in water temperature. The thermal junctions are installed in individual hypodermic tubing wells that are brazed in sections of the tubing for the cooling water. To ensure maximum thermal conductance and maximum electrical isolation between the thermal junctions and the well,

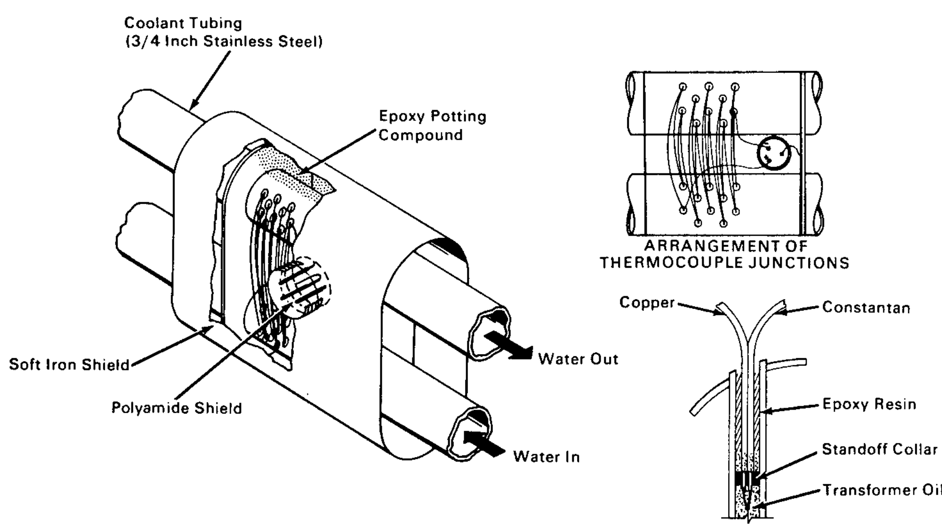


FIGURE 53.—Electrically shielded transducer with multiple thermocouple junctions used for measuring heat absorbed by coolant water from an arc-plasma generator.

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the junctions are submerged in transformer oil and then sealed in place with epoxy resin. Because of the high sensitivity of the thermopile, the temperature rise of the water can be accurately measured. If the water flow is known, the product of these two variables gives the rate of heat transfer to the cooling water.

An in-place calibration system for determining the heating rate in terms of kilowatts per inch of trace displacement of an oscillograph was developed for the transducer (ref. 72). The system consists of an electrical tubular heater connected in series with the cooling system of the arc-plasma generator and one leg of the heat-flux transducer. Before a test run of the generator, the heat-flux transducer is calibrated. Coolant water is circulated through the generator and transducer at a fixed rate; the water rate is monitored by a manometer that measures the pressure drop across the tubular heater. The dc power is supplied only to the heater at several kilowatt levels for the calibration run, and the corresponding signals from the transducer are recorded on the oscillograph. Thus, the calibration constant (kw/in. deflection) for the transducer is obtained and includes the product of the temperature rise of the transducer, the water rate, the scale factor of the oscillograph, and the conversion factor of the transducer. The test run with the arc-plasma generator is then made without changing the water rate. Recorded signals from the heat-flux transducer are converted directly into kilowatts (same units as input power) absorbed by the coolant water without any further computations or separate calibrations. This direct conversion saves data-reduction time and increases accuracy.

Radiant Energy Calorimeter

A significant contribution has been the development of a radiation calorimeter for measuring radiant energy in adverse environments by a NASA contractor, the Boeing Company-Launch Systems Branch (ref. 73). This calorimeter is an elliptical cavity radiometer that provides a wide view of 150 degrees solid angle coupled with a small exposed face (0.035-in.-diameter opening). As shown in figure 54, the radiant energy sensor is a differential Cu/Con thermocouple; it is isolated from the outside environment by a sapphire window that is continually purged. This radiometer was developed because the Saturn IC rocket had a soot-contaminated base area where the radiometer had to operate. A requirement of the radiometer was that it provide a small aperture and still retain the wide view angle of incident energy; the elliptical cavity achieves this because it focuses the incident energy on the radiant-energy sensor regardless of the angle of incidence. The purging system is probably the most significant feature of the radiometer. This feature was tested for 3 min with an oxyacetylene torch adjusted to produce heavy soot; the flame was directed at the aperture from varying angles with no deposition of soot on or in the radiometer. The instrument

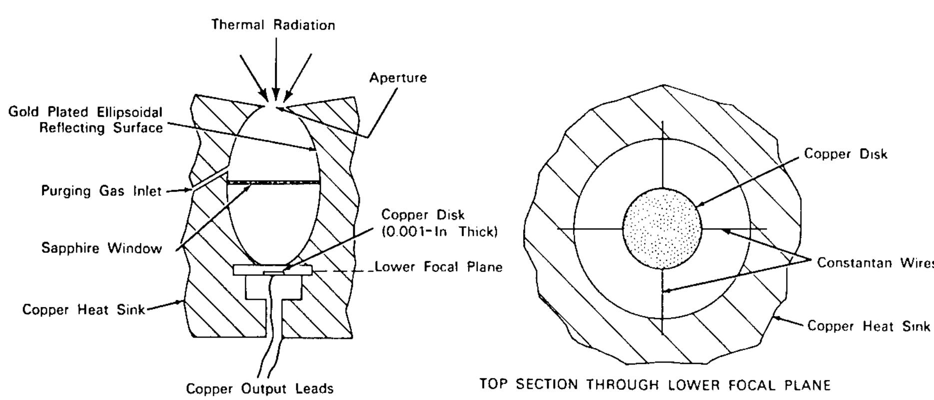
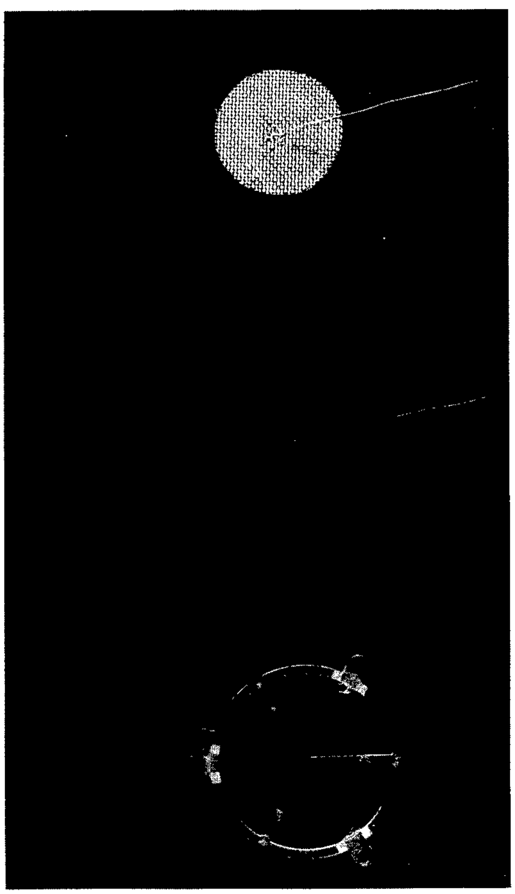


FIGURE 54.—Sensor, for measuring radiant energy in adverse environments, developed for Saturn IC engine studies.

successfully withstood 80 g's random vibration with superimposed sine wave for 5 min in all three major axes. The development of the instrument has continued through Phase II to provide flight capability of the instrument. The use of semiconductor sensors instead of the Cu/Con thermocouples has increased sensitivity for operation onboard rocket vehicles.

A calorimeter for measuring low-level radiant energy in the range of 0.06 to 3 solar constants, 0.007 to 0.37 Btu/ft^2/sec, has been developed at Langley Research Center (ref. 74). It is primarily suited to the measurement of the total energy that is radiated to a surface in vacuum. It also is valuable as a rapid-responding heat detector at normal pressure. Advantages of the calorimeter are the simplicity of data reduction and the independence of measurements from changes in specific heat and emittance of the sensor with temperature. Furthermore, it provides continuous readings of the radiant energy and is small and rugged.

The calorimeter consists of a mount, a compensating shield, and a sensor disk; fine-wire (3-mil) thermocouples are welded to the shield and the sensor disks (fig. 55). The top surfaces of the sensor disk and the shield are coated with a black paint to provide the surfaces with emittances as close as possible to unity. The surfaces underneath the disk and the shield are gold plated to have emittances as low as possible. To improve the performance of the calorimeter, the top disk is embossed as can be seen in the photographic section of



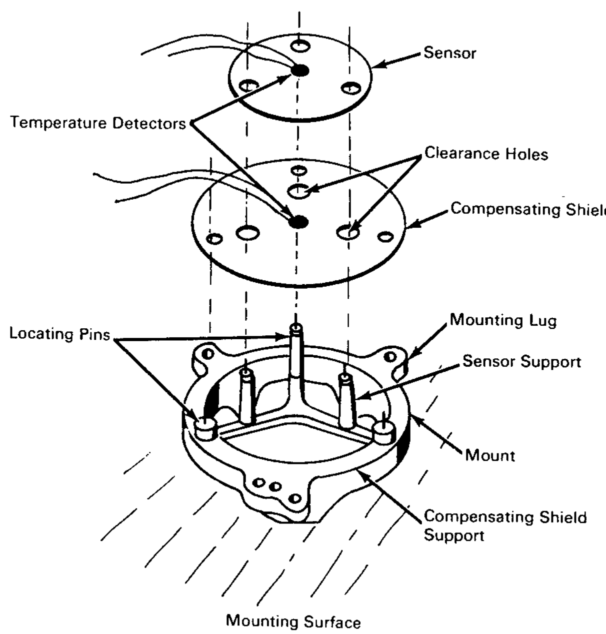


FIGURE 55.—Components of calorimeter that accurately measures radiant energy in a vacuum; gold-plated bottom surface of sensor and black-painted top surface of shield are shown with 3-mil thermocouples attached.

figure 55. For maximum accuracy, the temperature difference between the sensor and the shield is kept small and the heat losses to a minimum. The sensor disk and shield are supported by a plastic mount with low thermal conductivity that provides long heat-conducting paths between the test surface, the sensor, and the shield.

The calorimeter was developed because other calorimeters were not accurate enough for measurements of the low-level radiant energy levels in space when long-time, time-varying measurements were required, e.g., the measurement of solar exposure of a spacecraft orbiting the earth. Hence this calorimeter is ideal for measuring the radiant energy from objects in a vacuum chamber during scientific experiments.

Theoretical studies for the development of a practical radiant energy sensor using thermocouples in configurations of a radiation-balance have been conducted at the University of Michigan as a NASA program (ref. 75). The studies were of: (1) the derivation of mathematical equations governing the thermoelectrodynamic processes within the radiation thermocouple, (2) the derivation of mathematical equations describing the transient and steady-state behavior of the device, and (3) the determination of the minimum detectable power and optimum dimensions for the design of two proposed instruments.

Nuclear-Energy Sensor

A miniature intrinsic thermocouple (ref. 76) was developed at the Los Alamos Scientific Laboratory (LASL) to enhance the safety and control of all types of reactors. Refinements are now being made on Project Rover, the joint effort of AEC and NASA to develop nuclear rocket propulsion for space travel. This thermocouple represents a very important advance in this specialized area of instrumentation.

The theory of operation is that the basic reactor-fuel material itself provides the signal for the level of operation and the control of the reactor. The use of the fuel as part of the sensing element removes most problems associated with the mechanism of energy transfer required of other sensors. It provides a means of measuring nuclear energy directly as a temperature change. The thermocouple consists of a 16-mil bead of fissionable material (U–235, uranium carbide, etc.) with ½-mil Ch/Al thermocouple wires spot-welded to the bead (fig. 56). The ½-mil wires are welded to 10-mil support wires of the respective metals. The 16-mil dimension was selected for the bead since this is approximately a mean free path for a thermal neutron. The ½-mil wires minimize the heat leak from the thermal junctions that are at the interfaces of the welded wires and the bead. When the thermocouple is exposed to neutron and gamma radiation, the fissile bead will heat from both sources of energy. The temperature rise of the bead is sensed by the two thermal junctions.

The isolation of the neutron energy from an environment containing both neutron and gamma energies is accomplished by the use of a thermocouple arrangement with a gamma bucking circuit, as shown in figure 57a. Half-mil Ch/Al wires are welded to a fissile bead, but the opposite end of the Alumel (negative) wire is welded to a nonfissile bead. A second Chromel wire is welded to the opposite side of the nonfissile bead. Ideally, the two beads respond identically to gamma heating; in practice, this match does not exist. To circum-

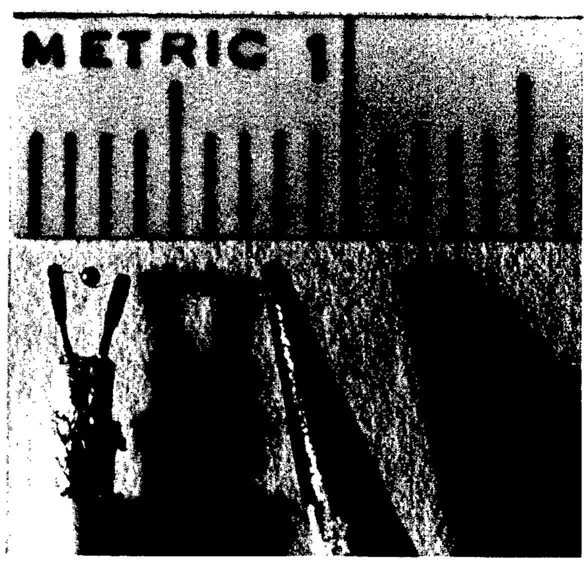


FIGURE 56.—Miniature intrinsic thermocouple developed for measuring nuclear radiant energy on Project Rover. Half-mil Ch/Al wires support a 16-mil U–235 bead.

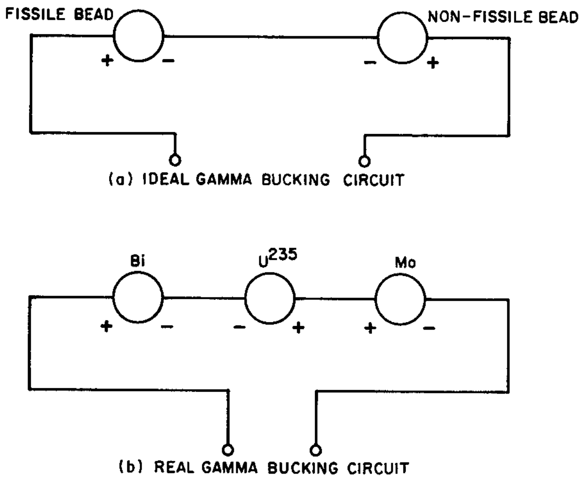


FIGURE 57.—Configurations of: (a) ideal, and (b) real intrinsic thermocouples for detecting only neutron radiation.

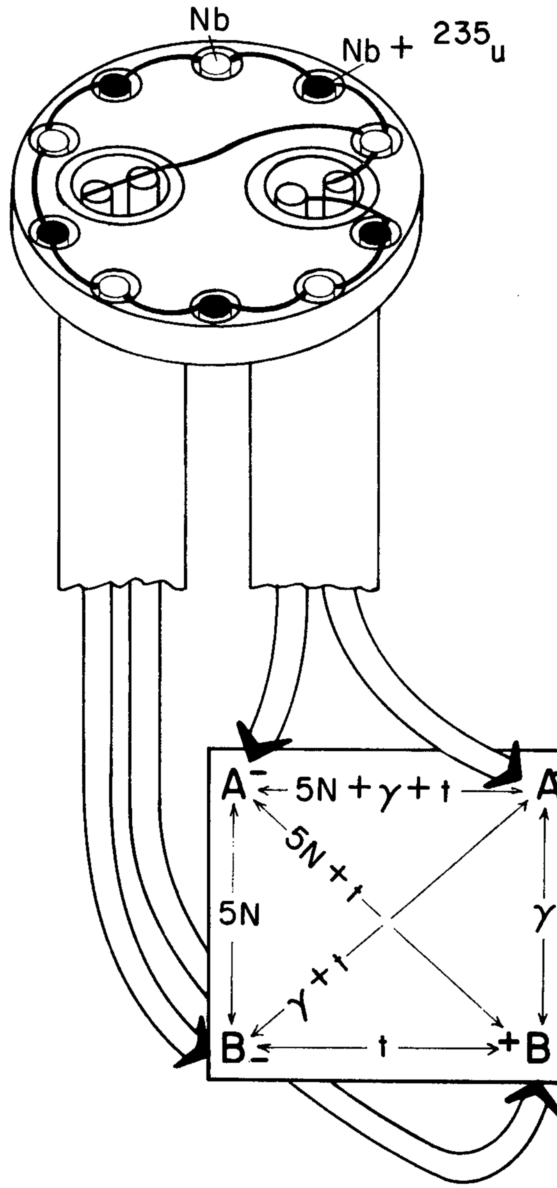


FIGURE 58.—UHTREX intrinsic thermocouple detector consisting of a thermopile of a series of 10 thermal junctions and four thermocouple leads that enable measurements of ambient temperature, heating effects of neutron flux, and gamma radiation.

vent this mismatch, another nonfissile bead could be added in opposition to the fissile bead to provide the desired matching of the gamma heating effects. Preliminary data indicate that the configuration in figure 57b would meet the requirements for providing a thermocouple capable of measuring only neutron radiation (ref. 77).

A thermopile of 10 intrinsic thermocouples, the UHTREX fission couple, has recently been developed at LASL (ref. 78). The detector uses niobium, the nonfissile material, as neutron "cold junctions" and 80-percent niobium and 20-percent enriched uranium–235 as the "hot junctions." Two metal-sheathed W–5Re/W–26Re thermocouple wires are the signal conductors and are connected to the detector as shown in figure 58. By reading the thermal emf's of the various combinations of the wires ($A+$, $A-$, $B+$ and $B-$), the contributions from the ambient temperature and the heat sources of neutron and gamma flux can be determined. This detector has withstood temperatures up to 1840° F for over 30 hr and given satisfactory readings at an estimated neutron flux of 10^{13} n/cm^2/sec.

The time responses of the miniature intrinsic thermocouples have been evaluated in numerous reactor burst (pulse) tests. In tests when a half-width of the energy pulse was approximately 35μ sec, the observed rise time of the thermocouple signal was approximately 40μ sec. Thus, the sensor has virtually zero time lag when sudden temperature increases are created by fission energy. With this characteristic property and the capability of self-compensating for ambient temperature and gamma heating effects, the intrinsic thermocouple has great possibilities for use as a "hot-spot" detector for conventional reactors. Continuing research at LASL is disclosing other possible applications in nuclear instrumentation.

POTENTIAL INDUSTRIAL APPLICATIONS

The various devices and sensors for measuring energy-transfer mechanisms described in this chapter have a high potential for industrial applications. The major areas where they can be used are in processes of high heat-transfer rates. The intrinsic thermocouple has limited value because the area of nuclear energy for which it was developed has limited applications.

Examples of possible industrial applications for the conventional devices of measuring heat transfer might include monitoring the heating rates of burners used in brazing or heat treating or softening operations on assembly lines; determining the efficiency of a bond between two metals in a production item by monitoring the heat flow through the bonded joint; determining the energy level of temperatures of gas flames which are too hot for conventional thermocouples, in the production of portland-type cements and chemical products such as ammonia and acetylene; and detecting the formation of scale or insulating layer on the fire-side surfaces of process chamber heating jackets.

CHAPTER 8

Special Techniques in Using Thermocouples

The success of a particular thermocouple application often depends upon the development of techniques for installation, check-out, and maintenance of the thermocouple and the associated circuitry and emf-measuring devices. Many of the features desired in a thermocouple system are obvious. Realizing these features under particular conditions, however, sometimes requires considerable effort.

Some of the more important guidelines for thermocouple applications are listed in reference 79:

(1) Lead wires should be run in grounded metal conduit

(2) Lead wires should have heat-resistant, weatherproof insulation

(3) All joints, except the thermocouple-measuring junction, should be soldered and insulated

(4) In systems of more than one thermocouple, selector switches should be double-pole type

(5) Lead wires should not be extended through hot zones that might damage insulation or cause shunting errors

(6) Indicators and recorders should be protected from dust and fumes, severe shock and vibration, or temperature extremes

(7) Thermocouples should be fabricated from wires that agree thermoelectrically with accepted calibration curves within appropriate limits and should be periodically tested for thermoelectric stability under the particular operating conditions.

Additional guidelines for the selection and installation of thermocouple wires and procedures for fabricating and checking thermocouples are enumerated in the ASA Standard on thermocouples for temperature measurements (ref. 1).

Rarely does a set of guidelines encompass all features required in a specific thermocouple application. Improved techniques, some designed for general thermocouple applications and some for special applications, have contributed significantly to recent advances. This chapter will emphasize special techniques and practices in the use of thermocouples at NASA centers.

Numerous practical methods will be described for attaching the thermal junction of a thermocouple to an object. The next section will give specific ways to solve the problem at the connection (between thermocouple wires rigidly held in metal sheaths and those in flexible insulated cables) where shorts or breaks can easily occur. In the final section, two techniques of passing the thermocouple wires through seals in vacuum chambers will be discussed. Practical methods will be given for fabricating thermal junctions and for storing metal-sheathed thermocouple wires; and a multipurpose instrumentation cable will be described.

THERMAL JUNCTION ATTACHMENTS

A common problem plaguing scientists and engineers is the attachment of the thermal junction to the surface of an apparatus, test model, or specimen. The technique used depends on the materials involved and the other requirements of the particular application. Various techniques are used throughout the NASA centers. Some are reported in the literature and in reports. Others have been accepted as common practice and have not been published; the writer identified some of these during interviews with engineers and technicians at the centers.

The Advanced Metals Research Corporation, under a NASA Headquarters contract, determined the thermal properties of some titanium carbide specimens (ref. 80). A very successful technique used to attach Ch/Al thermocouples to the specimens is described as follows: The titanium carbide specimen is mounted in a vacuum furnace with the thermocouple wires positioned above the spot on the specimen where they are to be attached. The specimen is heated to approximately 200° F above the melting point of the thermocouple wires, which are then brought against the specimens. The wires melt and diffuse into the specimen a specified amount. The resulting junction is sufficiently strong for handling, does not seriously contaminate the specimen, and has intimate contact with the specimen.

At Flight Research Center, Edwards, Calif., improvements in the technique of attaching thermocouples to the inner surface of the X–15 skin have reduced temperature errors significantly. Originally, the thermal junctions were attached to the skin by spot-welding the individual wires, approximately 1/16 in. apart, to the inner surface of the skin as shown in figure 59. In this situation, the metal of the skin became involved in the thermocouple circuit (ref. 81). This procedure proved to be satisfactory when there was no temperature difference within the 1/16 in. separating the two wires. However, significant temperature gradients have been experienced in some local areas of the X–15 structure, even within the distance of 1/16 in. In areas where high temperature gradients are anticipated, the thermocouple wires are now joined and spot-welded to the surface together (fig. 60). The former method of spaced-wire installation is still used in areas with low temperature gradients because of better installation quality control. An improvement in holding the insulated thermocouple wires in place is evident in figure 60. Metal foil strips are bent over the insulated wires and the ends of the strips spot-welded to the X–15 skin; these strips give a much greater contact area to the insulation than do the narrow hold-down wires previously used (fig. 59). During periods of vibration, the hold-down wires can break through the insulation and short the thermocouple wires at that point.

FIGURE 59.—Thermocouple installation located on the inside surface of the skin of the X–15 aircraft causes errors when the thermal junctions (1/16 in. apart) are in a region of large thermal gradient.

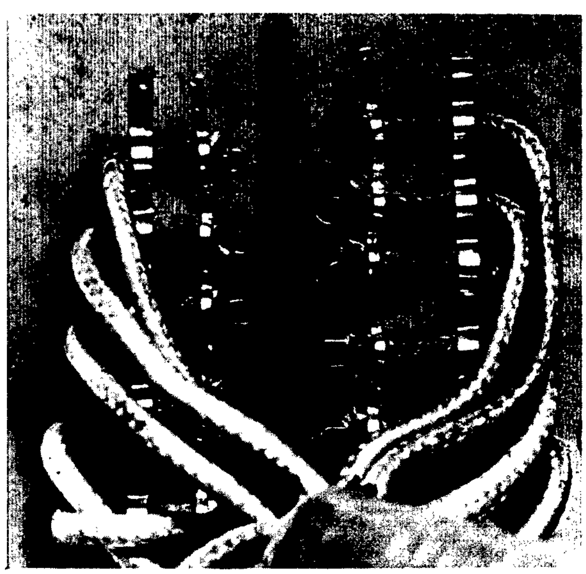


FIGURE 60.—Examples of thermal junction beads welded to the inside surface of the X–15 for temperature measurements in regions of large thermal gradients.

A method for installing thermocouple wires in locations not accessible to hand-welding techniques was devised by engineers at North American Aviation, Inc., under an MSFC contract (ref. 60). The method has been described previously in relation to obtaining maximum thermal contact between the thermocouple wires and the test object being instrumented. Basically, the method consists of the thermocouple wires being stripped and a thermal junction being formed by fusion welding of the wire ends to the bottom of a hole in the object. Fusion occurs when an electric arc is generated by the discharge of a bank of capacitors through the wires into the object.

Two techniques for attaching thermal junctions to surfaces of spacecraft components at JPL have been used on numerous NASA projects. The first deals with attaching Cu/Con or Ch/Con thermocouples to the spacecraft for testing in a space simulator chamber. Initially, the thermal junction is soft-soldered to a ⅜-in.-square sheet of copper foil. The foil is then cemented to the surface of the spacecraft with a silicone cement capable of withstanding at least 500° F. The thermal junction and the copper sheet are then covered with commercially available aluminized glass tape to complete the installation (fig. 61). The major advantage of this technique is that the junction can be peeled off without marring the surface.

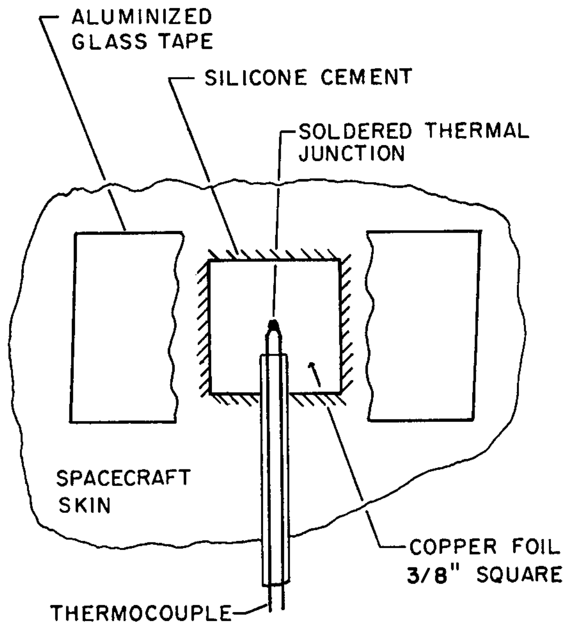


FIGURE 61.—Installation technique used at JPL for attaching thermocouples to the spacecraft skin.

The second technique provides a simple solution to a difficult spot-welding problem. Many Cu/Con thermocouples are used at JPL and are often welded to the test element. Because of the high thermal and electrical conductivity of copper, it is difficult to obtain reliable spot welds. However, copper alloys have considerably lower thermal and electrical conductivities; thus, the alloys can be reliably and easily resistance-welded. In practice, the instrumentation people make a fusion weld between the copper and constantan wires with an arc welder to form a bead of copper-constantan alloy. This thermocouple bead is then easily spot-welded to the test element.

Attaching thermocouple wires to a test item to which they cannot be spot-welded is usually a problem. One technique of attaching a surface thermocouple for operation above 2000° F already described consists of plasma-spraying a metal coating over the thermocouple wires to hold them on a pipe or tube.

For many applications involving cryogenic temperatures, wires are held on the test item with epoxy resin cement. This is a common practice at several NASA centers. At liquid hydrogen temperatures, the cement is a poor heat conductor between the thermocouple and the test surface. However, personnel at the Westinghouse Astronuclear Laboratory who work on nuclear engine studies of AEC and NASA add silver powder up to 35 percent by weight to the cement to improve the thermal conductivity of the cement. The modified cement has its thermal conductivity doubled without sacrificing its bonding strength. Thus, the thermal junction provides a more accurate temperature measurement than when it is cemented in place with the plain epoxy cement. The engineers have attached thermocouples to beryllium test pieces by drilling shallow, 50-mil holes in the pieces and then inserting the thermocouples coated with the modified cement (ref. 82). Other conductive powders such as copper or aluminum may provide the same thermal conductivity improvements. Many low- and room-temperature potential applications of this technique are found in industry.

Brazing thermocouple assemblies to the surfaces of test elements can be readily achieved in many applications. In some, however, the heat source is difficult to control unless the operator is highly skilled. A technique was developed at North American Aviation, Inc., on an MSFC contract, for applying small-diameter metal-sheathed thermocouples to the cooling tubes that form the liners of large rocket-thrust chambers (ref. 83). The control of the heat is particularly critical because of possible damage to the thin-walled cooling tubes. Small diameter metal-sheathed thermocouples are brought to the gas side of the thrust chamber through minimum-sized spaces between adjacent tubes. The thermocouples are bent to the contour of the tubes, and the thermal junctions of the thermocouples are resistance-welded to the tube. Because of questionable reliability of the welds during the severe vibrations and possible excessive heating of the sheathing during engine firing, the junctions and the exposed sheathing are brazed to the tube surfaces. A thin layer of powdered brazing filler and flux is applied to each area, and the temperature at each area is slowly increased by a quartz lamp heater. The thermal emf from the thermocouple is continuously monitored during the heating as indicated in figure 62. Since the melting temperature of the brazing material is known, the heater can be manually controlled so that the thermocouple and the tube surfaces are not heated above the brazing temperature. When the powdered brazing material does not initially adhere to the surfaces to be brazed, a dam is built of asbestos fibers to confine the powder.

This technique of using the signal from the thermocouple to prevent excessive tube-wall temperatures has enabled a semiskilled technician to make excellent thermocouple installations that are reliable and consistent in quality.

THERMOCOUPLE WIRE CONNECTIONS

The metal-sheathed thermocouples have been used in a vast number of applications at virtually all NASA centers. A former problem with these thermocouples was the connection between the rigid metal-sheath section and the flexible lead wire. However, special connection techniques have been worked out to solve the problem. The main purpose of these techniques is to prevent the flexibility of the lead wires from being transmitted to the relatively rigid thermocouple wires of the metal-sheathed assembly. Almost universally, the lead wires are resistance-welded or soldered to the wires from the sheathed assembly where they protrude from the metal sheath. If flexure is subsequently permitted at this location, the wires will either be shorted to each other or break.

One of the first designs to be developed at Langley Research Center has proved to be very successful (ref. 84). A step-by-step assembly of a thermocouple is illustrated in figure 63. The wires are extended about ¼ in. from both the flexible duplex cable and the rigid metal-sheath thermocouple and are stripped

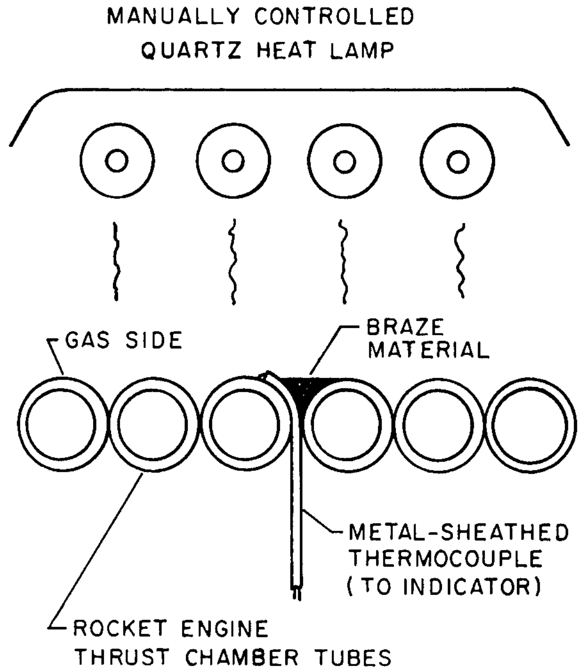


FIGURE 62.—Arrangement for producing and monitoring brazing temperatures in critical area while installing small metal-sheathed thermocouples to thin-walled tubing.

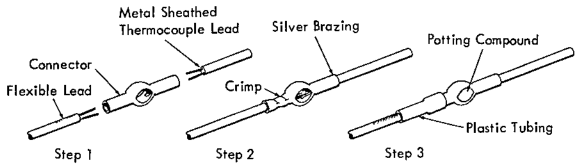


FIGURE 63.—Assembly details of connecting metal-sheathed thermocouple wires to flexible lead wire.

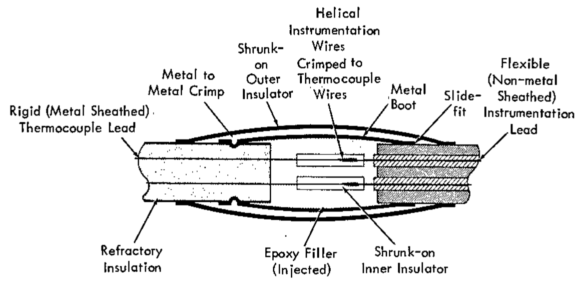


FIGURE 64.—Mechanical connection of metal-sheathed thermocouple wires with wires of flexible duplex cable.

clean. A connector, fabricated from a slightly larger metal tube, is split at the center of its length and spread to make an eyelet. The end of the metal-sheath thermocouple is slipped into the connector until the two wires are visible in the eyelet and the connector is silver-soldered to the sheath. The flexible duplex cable is inserted at the opposite end of the connector until its bare wires are positioned over their respective mates. The connector is then mechanically crimped to hold the duplex cable rigid. The pairs of bare wires are then resistance-welded together or silver-soldered with a miniature torch. The eyelet is potted with clear epoxy or other type of resin to completely immobilize the wire connections. Use of a length of heat-shrinkable plastic (PVC) tubing over the end of the connector and a ½-in. distance along the flexible duplex cable further reduces the chances of breaking the duplex cable where it emerges from the metal tubing of the connector.

A similar technique was developed on an AEC–NASA nuclear propulsion program at Westinghouse Astronuclear Laboratory (ref. 85). The connector has a small diameter and requires no soldering or brazing. The details of the connector are given in figure 64. First, the wires from the metal-sheathed thermocouple and the wires of the flexible duplex cable are stripped. A metal sleeve with an i.d. slightly larger than the o.d.'s of the thermocouple, and the cable is slipped onto the cable for subsequent use. Each of the bare wires of the duplex cable is tightly spiraled into a helical coil just larger than wires from the thermocouple. A short piece of heat-shrinkable plastic is slipped over each of the bare thermocouple wires protruding from the metal-sheathed assembly. The thermocouple wires are inserted into their respective helical coils from the duplex cable; the coils are crimped to form an effective connection. The individual heat-shrinkable plastic sleeves are slipped over the crimped connections and shrunk on. The metal sleeve is pulled back over the connections and crimped onto the metal sheath of the thermocouple to form a bridge between the metal sheath of the thermocouple and the cable. Epoxy cement is injected into the cavity by a hypodermic needle inserted along the side of the duplex cable; the epoxy filler provides rigidity to the connection and, more important, a moisture-proof and corrosion-proof seal. The connection area is covered by heat-shrinkable plastic to give added protection against breakage of the flexible duplex cable where it emerges from the metal sleeve. This connection technique has provided a transition section from the metal-sheathed thermocouple to the flexible cable with a minimum diameter and protection from moisture and corrosion; its main disadvantage is the temperature limitation imposed by the plastics that are used. The assembly is simple to produce because reliable connections can be made by semiskilled personnel with a minimum of instruction.

Another connector was developed at Aerojet-General Corporation on contractual work for AEC–NASA Space Nuclear Propulsion Office (ref. 86). This connector is all plastic and might prove advantageous when many thermocouples are being produced. There is a temperature limitation, however, because of the use of plastics (polycarbonate) and a slightly awkward side connection instead of a coaxial connection (fig. 65). The wires from the sheathed thermocouple and the instrumentation cable are stripped, and the respective wires are soldered together and placed in the bottom half of the molded plastic insulator. The top half is put on and a protective cap is slipped over the insulator halves. The assembly is dipped into methylene chloride, which bonds it together. The metal-sheath thermocouple must be tightly cemented in the insulator to prevent it from becoming twisted and its wires from breaking or shorting.

The problem of metal-sheathed thermocouples twisting in a connector has been eliminated by Instrument Shop personnel in the MFSC Instrument Development Branch Test Laboratory (ref. 87). As shown in figure 66, a delta-wing-shaped bracket is silver-soldered to the end of the metal-sheathed thermocouple. This bracket is then clamped between the halves of the connector. The bracket rigidly holds the connector and the thermocouple together so there is no possibility of the wires being twisted or pulled in the connector. In fact, the connector would have to be nearly destroyed before the wires could be broken or shorted together.

The connection of 1-mil thermocouple wires to flexible lead wires in a thermocouple probe can be extremely difficult since the slightest motion can cause failure. A simple, practical manner in which to make this connection was devised at Langley Research Center (ref. 88). A sectional view of the connection is presented

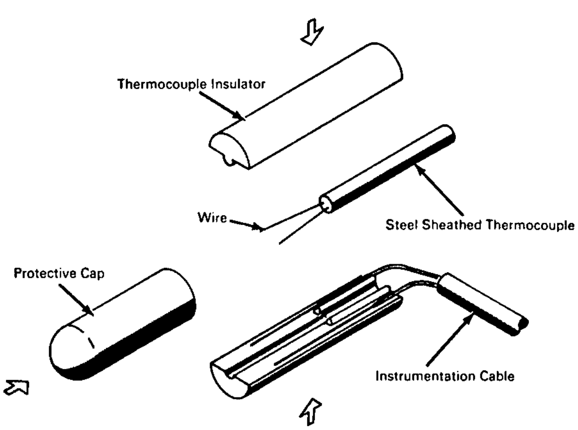
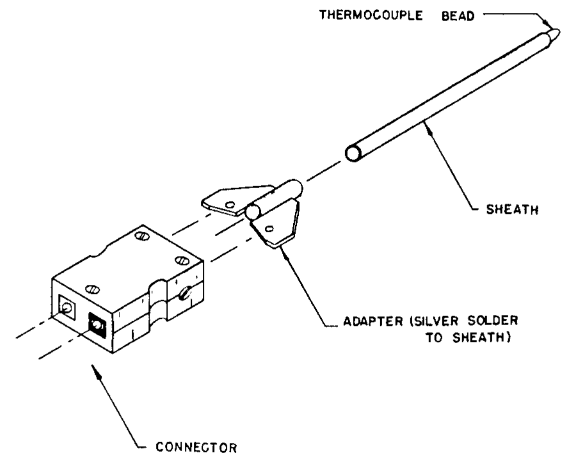


FIGURE 65.—Plastic connector for metal-sheathed thermocouples and flexible duplex cable.



thermocouple to prevent the thermocouple from twisting in connector.

in figure 67. Initially, the 1-mil wires are cemented in a two-hole ceramic insulator of the appropriate length. The bare-wire ends from the flexible cable are cemented in a larger two-hole ceramic insulator, as illustrated in figure 67a. Because the lead wires extend through the ceramic insulator, they are exposed in the grooves of the insulator. The exposed wires are flattened with a file and polished to provide surfaces for the resistance-welding of the 1-mil wires. A middle tube is prepared (fig. 67b), and both ceramic pieces containing the fine and large thermocouple wires are inserted and cemented so that the wires overlap in the cut-away portion of the middle tube (fig. 67c). The fine wires are then welded to the large wires with a miniature resistance welder. A cover tube is cemented over the rear end of the middle tube to cover the cut-away portion and to reinforce the flexible lead wire as it protrudes from the probe (fig. 67d). Thus, the connections between the fine and large wires are completed in a probe which is rugged and easily used.

METAL-SHEATH THERMOCOUPLE TECHNIQUES

Miscellaneous techniques and innovations are continually being developed. Several techniques for handling metal-sheathed thermocouples will be described here.

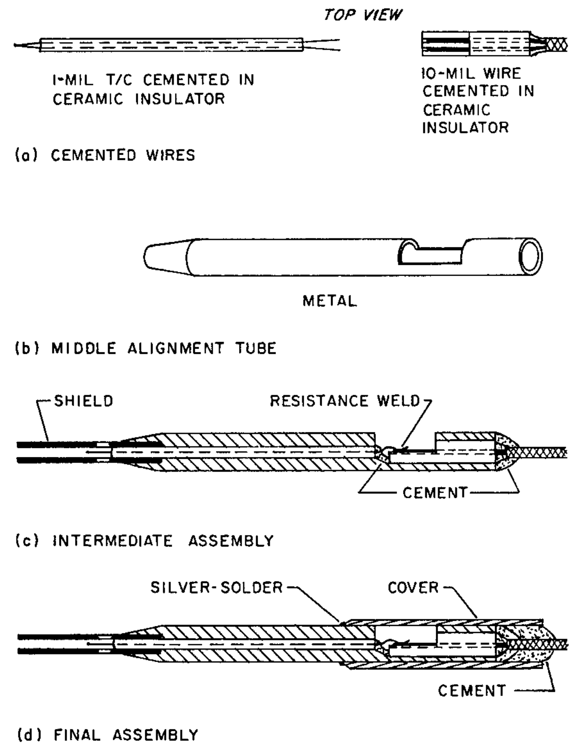


FIGURE 67.—Details of connecting 1-mil thermocouple wires to flexible lead wire.

Vacuum Seals

The measurement of temperatures in an ultra-high vacuum ($<10^{-9}$ torr) chamber may present problems because of the passage of the thermocouple through the vacuum seal. At several NASA centers, hermetic glass seals with tubes instead of the solid pins have been ordered from vendors. Bare wires from metal-sheathed thermocouples are threaded through the tubes and silver-soldered at the outside end of the tubes. Ceramic insulators are slipped over the wires and into the opposite ends of the tubes to prevent the thermocouple wires from touching the tubes. The tubes are usually made from a low thermal-expansion nickel-iron alloy to have a thermal expansion that matches the glass or ceramic seal. If the thermocouple wire touches both ends of the tube, an erroneous signal is generated when the ends of the tubes are at different temperatures. Many vendors now supply these hermetic seals.

Metal-sheathed thermocouples with sealed thermal junctions are commonly used in ultra-high vacuum chambers. In a small space simulator at JPL, the sheathed thermocouple is passed through a port by means of a copper gasket that is normally used as a pinch-off evacuation gasket. The copper tube in the gasket is silver-soldered to the thermocouple sheath, as indicated in figure 68; the gasket is installed as usual in the flange of the chamber. This technique has proved very satisfactory.

Thermal Junction Fabrication

The ends of thermocouple wires are often butt-welded to form the thermal junction for special thermocouples. The MSFC Instrument Shop developed a technique of forming a more perfect interface between the two wire ends for the butt-welding procedure. A holding block supports the thermocouple wires from a metal-sheathed or a ceramic-insulated thermocouple to allow a diamond-slitting saw to cut the wires. As shown in figure 69, the thermocouple is placed on the V-shaped groove; the wires, clamped by a screw on each side, pass around the small post on the block, one from each direction. The slitting saw cuts both wires at the same time; therefore, the ends are flat and matched for the butt-welding operation. Because the surfaces for the weld are matched, reliable welds (and, as a consequence, reliable thermal junctions) are made.

The fabrication of a sealed thermal junction on the end of small-diameter, metal-sheathed thermocouple material can be difficult. At

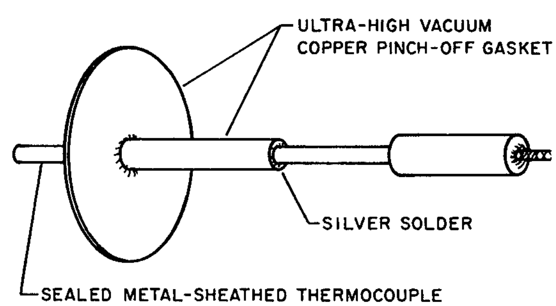


FIGURE 68.—Vacuum feed-through technique for introducing a sealed, metal-sheathed thermocouple into an ultra-high vacuum chamber at JPL.

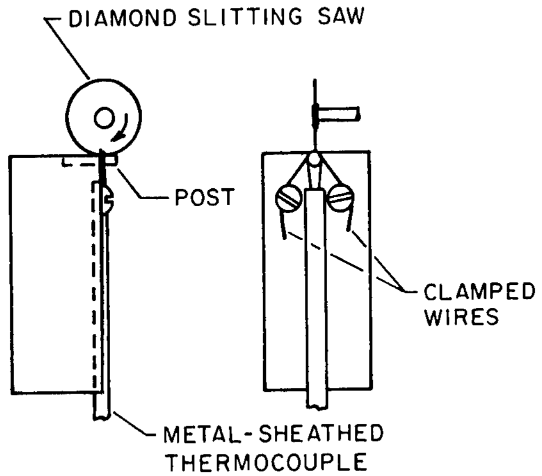


FIGURE 69.—Holding block for forming matched interface between two wires for butt-welding.

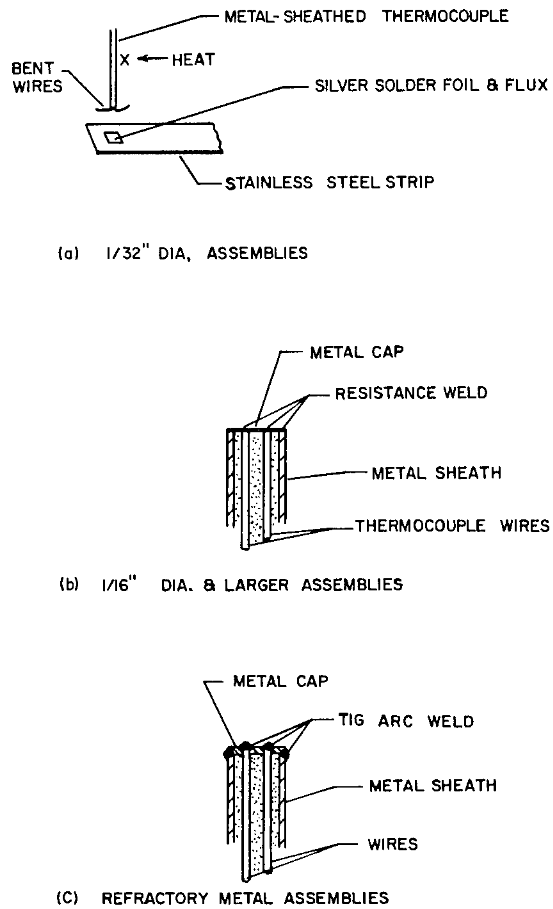


FIGURE 70.—Techniques of forming thermal junctions and sealing metal-sheathed thermocouples used at Langley Research Center: (a) 1/32-in.-diameter assemblies, (b) 1/16-in.-diameter and greater, and (c) refractory metal assemblies.

Langley Research Center, the following capping procedure is successful with 1/32-in.-diameter material. The end of the metal sheath is removed to expose 1/8-in. wire lengths. The wires are cleaned and bent radially outward (fig. 70a). A strip of 2-mil stainless-steel foil is used as the capping material; a small piece of strip-silver solder and a drop of flux are placed on the foil. The metal-sheathed assembly is heated to dull red starting about 1/2 in. from its end at point *X*; the heated zone is then moved toward the end to be soldered. This heating drives off absorbed moisture and excess gas in the insulation powder. The end of the assembly is held near the stainless-steel foil so the torch will heat the silver solder. As it melts, the end of the assembly is placed on the silver solder and the torch is removed. The excess foil is trimmed and the end is filed to the metal-sheath diameter to complete the procedure.

Another technique used at Langley on 1/16-in.-diameter assemblies and larger is suggested by figure 70b. The procedure consists of resistance-welding a foil of the appropriate material onto the end of the assembly. The ends of the wires must be clean to obtain satisfactory welds between them and the underneath surface of foil. The foil is welded first to the ends of the wires and then to the end of the tubular sheath. A gas-tight seal is difficult to obtain in this type of capping without special welding electrodes.

When refractory metals are used in the thermocouple assembly, resistance welding may not be reliable because of the difficulty of removing oxygen from the welding environment. In such cases, the capping technique indicated in figure 70c has been successful. The sheath is cut back to expose 1/16-in. lengths of the thermocouple wires. A cap, 10 to 20 mils thick with the diameter of the sheath, is prepared from the same type of metal as the sheath metal. Two holes are drilled through the cap to allow the wires to protrude through it. The cap is then arc-welded onto the sheath with inert gas protection and the ends of the wires are fused into the cap.

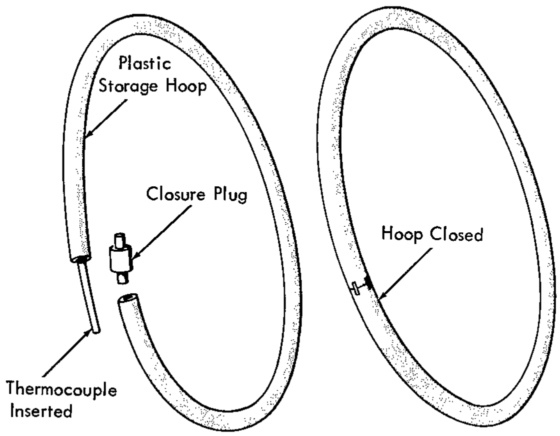


FIGURE 71.—An inexpensive storage container for expensive metal-sheathed thermocouple wire improvised from hollow "Hula Hoops."

Storage of Metal-Sheathed Thermocouples

An inexpensive storage container for expensive metal-sheathed thermocouple wire has been improvised from hollow plastic hoops ("Hula Hoops") sold by variety stores (ref. 89). To use the hoop, it is opened at the closure plug, and the wire is inserted. The hoop is then closed by replacing the plug, as illustrated in figure 71. This idea has been used for the coiled sheathed thermocouples at the Westinghouse Astronuclear Laboratory. Different colored hoops are used for the different types of thermocouple wire being stored. Excellent protection is given to the expensive thermocouple wire in this manner.

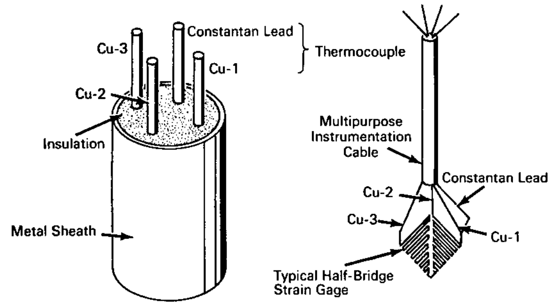


FIGURE 72.—Use of multipurpose cable to combine signals from thermocouple and other sensors.

Multipurpose Metal-Sheath Cable

A simple but often overlooked idea in providing instrumentation to a test fixture or a model is the possibility of combining conductors of several detectors or transducers in the same instrument cable. Remote monitoring of the temperature of a strain-gauge or pressure transducer can be readily accomplished by using a Cu/Con thermocouple. When metal-sheathed instrument cables with several conductors are used, the cables are usually custom-made. Hence, the additional cost of inserting a constantan wire in the cable is not great. As suggested in figure 72, the copper lead wire to a strain gauge is combined with the constantan wire to form a thermal junction at the strain gauge. Thus, the temperature can be measured without an additional thermocouple cable (ref. 90).

CHAPTER 9

Thermocouple Circuits and Reference Junctions

The accurate measurement of temperatures with a thermocouple is dependent not only on the proper thermocouple probe but also on adequate check-out circuits and reference junctions. The circuits used to check thermocouples to ensure proper functioning are particularly important in complex instrumentation systems such as a rocket vehicle and its payload. The second section of this chapter will enumerate several means of providing reference junctions for thermocouple applications.

THERMOCOUPLE CHECK-OUT CIRCUITS

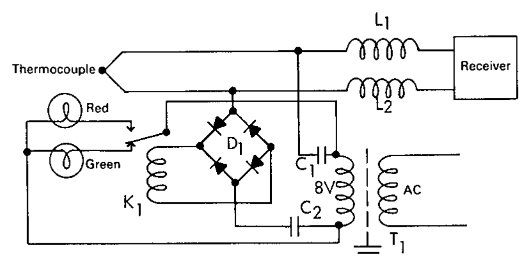
Thermocouple check-out circuits are designed in a variety of ways, three of which will be described in this section. They are a continuity monitoring circuit, an automatic check-out circuit for thermocouples, and a manual check-out circuit for thermocouples.

Continuity Monitoring Circuit

A simple method of monitoring the continuity of a thermocouple without disconnecting the leads has been developed at MSFC (ref. 91). The technique was devised to monitor thermocouple sensors aboard the Saturn vehicle during static tests. Continuity had previously been checked by disconnecting the thermocouple leads and attaching an instrument. This was time-consuming and could not be done while the vehicle was under power.

The testing circuit (fig. 73) provides an indication of the continuity of the entire thermocouple circuit, including lead wires and reference junction. The thermocouple is capacitively connected to the secondary of a stepdown power transformer. The transformer provides a low voltage to operate a relay connected to the thermocouple circuit through capacitors C_1 and C_2. The capacitors prevent the thermal emf of the thermocouple from being shorted by the transformer winding. The inductances L_1 and L_2 protect the recorder from the 60-Hz transformer voltage. The ac thermocouple current is converted by the bridge rectifier to dc for operation of the relay. When continuity exists in the thermocouple circuit, the output voltage of the transformer is applied across the rectifier to activate the relay that lights the green indicator lamp; discontinuity in the thermocouple circuit opens the relay, that turns on the red lamp.

Because the thermocouple signal is very low compared to the voltages of the monitoring circuit, a shielded power transformer must be used. Furthermore, capacitance in the thermocouple conductor lines must not be large enough to enable ac leakage to trip the relay. In the



C_1, C_2	2 Microfarads, 400 volts (paper)
L_1, L_2	200 Henries
D_1	Bridge Rectifier, 4 each 1N649 Diodes
K_1	Relay, Sigma 4R5000S (or equivalent)
T_1	Transformer, Power, Stancor P-1834-3 (or equivalent)

FIGURE 73.—Circuit for continuous monitoring of the continuity of thermocouples.

breadboard testing of the monitor, a capacitance as large as 0.2 μF could be used without operating the relay. Effectiveness of the isolation of the monitor circuit from the thermocouple circuit was demonstrated by turning the monitor power on and off without any change in the signal at the recorder.

Resistance of the thermocouple circuit may vary between wide limits. Grounding the thermocouple does not affect operation of the monitoring circuit. Sensitivity of the monitor can be adjusted by changing the hysteresis of the relay or by adjusting the ac voltage. Components used in the construction of the monitor are all commercially available electronic parts.

Automatic Check-Out Circuit for Thermocouples

A circuit for automatically checking out thermocouples was developed on Project Fire, the project for determining heat transfer to reentry packages at velocities slightly higher than lunar spacecraft reentry velocities. The work was conducted by Republic Aviation Corporation under contract to Langley Research Center (ref. 58). The circuit was used for testing the 1-mil thermocouples in heat-transfer gauges installed in the beryllium heat shield as described in chapter 6. The heat shield of Fire II had 148 of these fine-wire thermocouples; hence, it was essential to have a quick system to test the thermocouples.

The system that evolved is shown schematically in figure 74. Essentially, the circuit applies a constant current from a battery and a resistor across each thermocouple; the voltage across the thermocouple loop is directly proportional to the resistance of the thermocouple. The magnitude of the current is adjusted with a variable resistor to a value that gives full-scale deflection of the data-system recorder for the highest thermocouple circuit resistance to be measured. The signals from the 144 thermocouples are periodically sampled by a commutator switch; each signal pulse is amplified and conditioned by a pulse duration modulation (PDM) unit, part of the telemetering system.

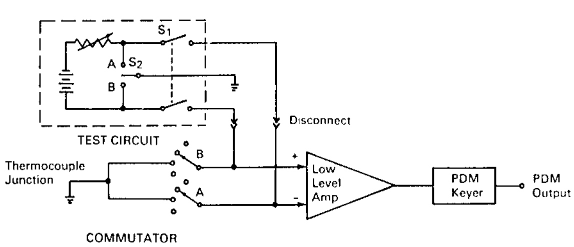


FIGURE 74.—Circuit to check resistance and continuity of each thermocouple wire or both wires automatically during preflight testing of Project Fire reentry packages.

In operation, the thermal emf signals from the thermocouples are obtained with the switch, S_1, open to confirm that there are no stray signals on the thermocouple circuits. Next, S_1 is closed with S_2 in the neutral position and a sweep of the thermocouple signals recorded; the signals are calibrated in terms of thermocouple loop resistance. In case a thermocouple wire is broken (in an installation having grounded thermal junctions), S_2 can be engaged in position A and a sweep of the thermocouple signals can be made to determine if the A wire of the thermocouple is broken. In a similar manner, the B wire of the thermocouple is checked. Because the signal is proportional to the resistance of the thermocouple, a low resistance as well as a high resistance is indicated. Hence, the check-out instrument is also valuable in detecting a thermocouple short.

Manual Check-Out Circuit for Thermocouples

A manual checking circuit for thermocouples was originally developed by the Boeing Company, Seattle (ref. 92). The instrument was designed to check thermocouple circuits for thermal contact, electrical continuity, and correct polarity without causing temperature changes at the thermocouple junction. The usefulness of the checking circuit was increased by a modification made by the MSFC Instrument Development Section, Test Division (ref. 93). The modification consisted of replacing the standard rotary potentiometer by a dial potentiometer so that the dial could be read directly and recorded.

The instrument circuit is shown in figure 75. Operation of the circuit is based upon the resistance difference of the thermocouple wires.

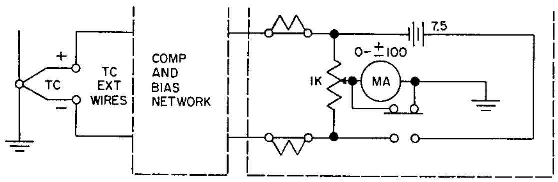


FIGURE 75.—Instrument circuit for manually checking the condition of thermocouples with grounded thermal junctions.

The circuit includes a potentiometer that completes a bridge, a zero-center microammeter connected between the potentiometer wiper and the thermocouple ground, a battery for resistance-bridge excitation, and a pushbutton to protect the microammeter and prevent unnecessary battery drain. When the instrument is used, the dial reading of the potentiometer is constant for a particular type of thermocouple and is independent of the length of the thermocouple wires and of the reference junction temperature. The instrument can detect the proper polarity of the thermocouple. When extension wires are used with the thermocouple, the dial reading shows whether or not the extension wires are properly connected to the thermocouple wires. When poor contact exists between the thermal junction and ground (indicating poor thermal contact), the instrument has no deflection. A broken thermocouple, or an open circuit with the thermocouple still grounded, results in excessive deflection—clockwise if the open circuit is in the high-resistance wire and counterclockwise if the open circuit is in the low-resistance wire. Undesirable grounds or shorts also give distinctive deflections.

The tester enables grounded-thermocouple installations to be checked rapidly. However, since many thermocouple circuits are ungrounded, the practical applications of the check-out instrument may be limited.

REFERENCE JUNCTIONS

The reference junction of a thermocouple circuit is normally considered as an afterthought. In many applications, the indicating instrument has a compensation coil for the reference junction. In other applications, commercially available reference-junction ovens are used. There have been several applications where commercial reference junctions were impractical. Consequently, innovations have been made at several NASA centers. These include three methods of providing the desired reference junctions: (a) a floating reference junction, (b) a zone box, and (c) a reference-junction oven for in-flight service.

Floating Reference Junction

At GSFC a floating reference junction* was devised for a multitemperature measuring system in which the measuring thermal junctions were a considerable distance from the reference junctions (ref. 94). A reference junction unit for all the thermocouples would have been costly and would have added to the complexity of the system. The system that was used is shown in figure 76; it consists of Cu/Con thermocouples with the floating reference junction. All the thermocouple cables have their reference junctions thermally connected to an insulated copper terminal block. This terminal block is, thus, the floating reference junction.

Copper lead wires from the measuring junction are brought to bank *A* of a multipoint switch and the wires from the floating reference junction to bank *B*, as indicated in figure 76. A single Cu/Con thermocouple is connected to the floating reference-junction block to sense its temperatures; the reference junction, a commercial unit, for the single thermocouple is maintained at a constant temperature. The copper lead wire from the measuring thermal junction of the single thermocouple is connected to the wiper arm of bank *B*; the other wire is connected to the negative terminal of a millivolt recorder or other appropriate instrument. The wire for the positive terminal comes from the wiper arm of bank *A* of the switch.

When the switch is placed in any position, the test thermal junction, the reference thermal junction, and their corresponding junctions on the floating reference junction are all connected in series. The thermal junctions on the floating reference-junction block are at the same tem-

*"Floating" means that the temperature of the junction is not fixed.

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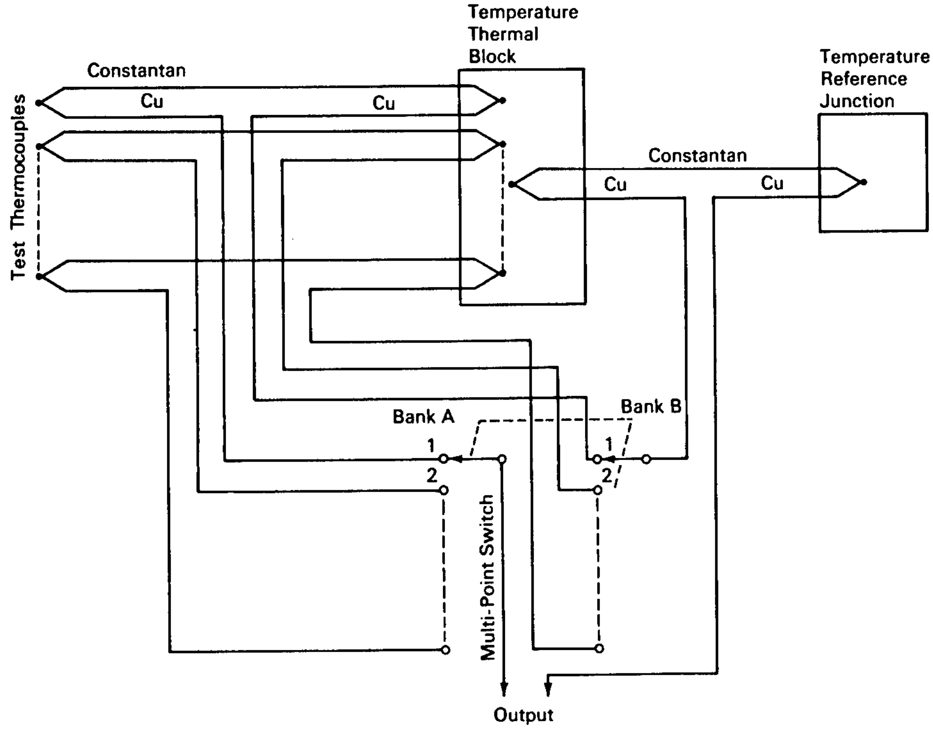

FIGURE 76.—Floating reference junction circuit that enables use of many thermocouples with one reference junction.

perature but are connected in opposition; hence, their signals cancel each other, and the signal indicated by the millivolt recorder is the difference between the test and the reference junction in the commercial unit. The floating reference-junction block can be at any temperature, but it must be uniform. Although the circuit appears rather complicated, it is actually simple to install and use.

Zone Box

The "zone box" is a special temperature compensation network designed for operation in the Jupiter and Saturn vehicles. It was developed because of the difficulty in maintaining a reference junction temperature for thermocouple installations in rocket-vehicle systems. Providing stable temperature zones in flight hardware has proved undesirable in most cases because of limitations on the design flexibility of the hardware. Alternate approaches to reference junction design include:

(1) Monitoring the temperature of the junction before flight and assuming that it does not change appreciably during flight

(2) Monitoring the reference junction temperature during flight

(3) Compensating for reference junction temperature changes during flight so that no error is introduced into the system under any conditions.

The third approach has been used on the Jupiter and Saturn vehicles. The development of the zone box and bridge circuits for temperature compensation was accomplished by MSFC (ref. 95).

The schematic and configuration of the zone box are shown in figure 77, and the bridge circuit used on the Saturn vehicle is illustrated in figure 78. The reference junction is located in the zone box where the thermocouple wires are attached to the vehicle network wires. A small-resistance thermometer is placed in thermal contact with the reference junction. The resistance element is selected to have a positive coefficient of resistance with respect to temperature. It forms one element of the bridge

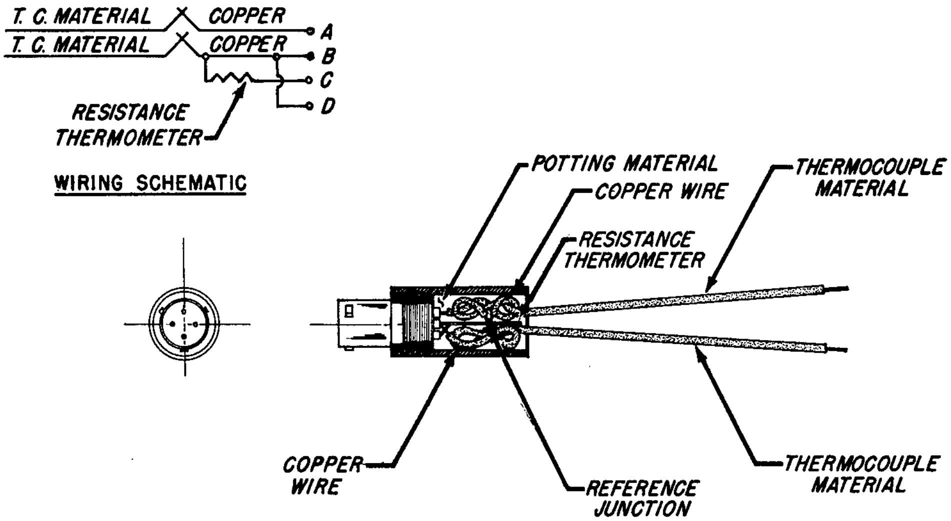

FIGURE 77.—Schematic and configuration of the "zone box" used on Saturn rocket vehicles to provide automatic-thermocouple reference junction compensation.

and attenuates the output emf of the bridge to make it the same as that of the reference junction. The bridge emf cancels the change of the reference junction emf that would result from a change of the reference temperature; this cancellation effectively creates a constant reference emf. Thus, the output of the system is the true emf of the hot junction, regardless of the temperature of the reference junction.

The original bridge circuit developed for Jupiter had a sizable error caused by uncompensated lead wire resistance. The use of three connections from the zone box to the bridge circuit minimized the effect of lead wire resistance. The addition of the resistance of the third wire tends to cancel the effect of the lead resistance of the second wire since the two wires are in adjacent elements of the bridge. The cancellation is only partial since *RD* is much larger than *RC*. However, the active element of the bridge contains only the resistance of the second wire; therefore, the lead wire resistance is reduced to one-half that in the Jupiter design. The result of this modification is a reduction of an order of magnitude in the measurement error at the extremes of the operating range of the zone box. The maximum error from −20° F to over 220° F is 0.5° F; the errors in the normal operating range of 50° to 200° F are no greater than 0.2° F.

Environmental specifications for the zone box on the Saturn vehicle call for operation from −5° to 250° F. Present units can operate continuously from −150° to 480° F with prototype units capable of withstanding continuous temperatures in excess of 1000° F. Potting material is carefully selected to assure that differential thermal expansion does not strain the resistance element and that thermal lag between the reference junctions and the resistance grids is minimized.

Reference Junction Oven for In-Flight Service

The method of providing a thermocouple reference signal at the Flight Research Center

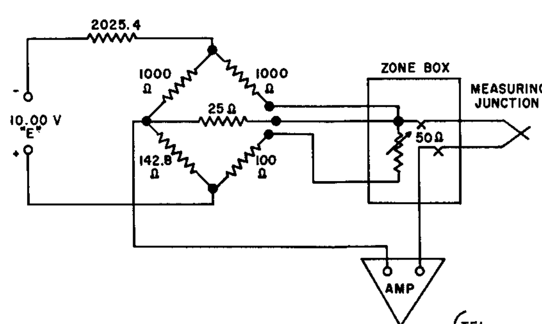

FIGURE 78.—Bridge circuit fused on board the Saturn in conjunction with the "zone box."

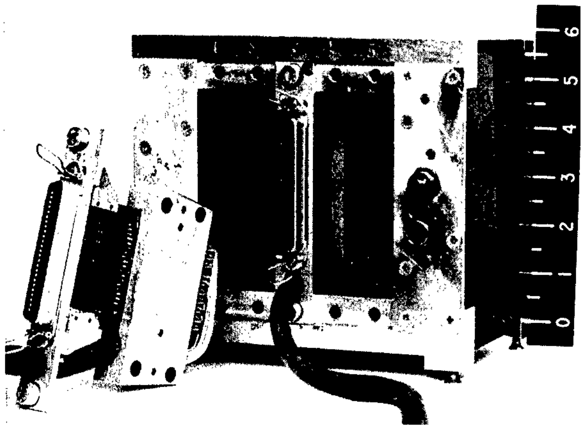

FIGURE 79.—Thermocouple reference oven developed at Flight Research Center for in-flight service on the X–15 aircraft (with a capacity of 100 reference junctions).

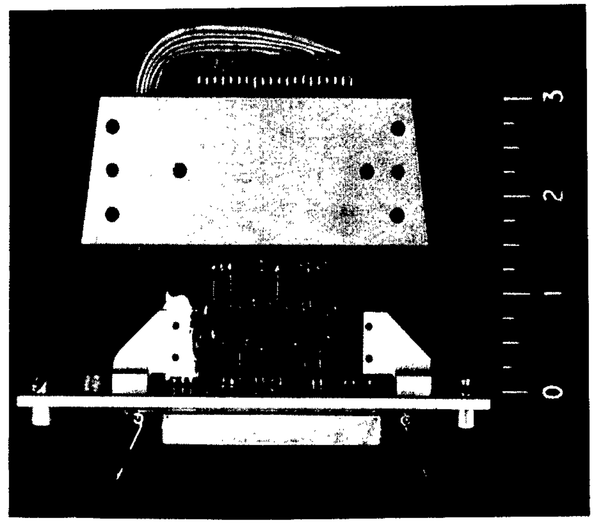

FIGURE 80.—Reference junction insert with trimming resistors for constant circuit resistance.

involves a special lightweight oven that can be used onboard the test vehicle. This method follows the conventional approach since the reference thermal junction is maintained at a constant and known temperature. Commercial units could not be used because they were too large and heavy for flight hardware; as a result, the engineers developed the oven for their requirements (ref. 96). Photographs of the oven and the reference junction inserts are shown as figures 79 and 80.

The oven consists of an insulated case with tapered slots in aluminum plates at the top and bottom of the furnace interior. Oven temperatures are controlled with a thermostat that turns on and off a heater tape surrounding the aluminum plates. Up to five inserts can be placed in the oven. Since each insert has a capacity of 20 thermal junctions, the oven can serve 100 reference junctions in a volume of approximately 6 by 6 by 8 inches.

The inserts (fig. 80) consist of an aluminum block with inclined top and bottom edges to make maximum thermal contact with the oven interior plates. The block encloses the reference junctions which are located on each side of a rigid electrical insulation board. The thermocouple wires come from the various locations in the vehicle to the oven insert. From the insert, a disconnect is provided for the copper-conductor cable to a galvanometer or telemetering equipment. Each thermocouple circuit has a trimming resistor, as seen along the side of the insert, to allow the resistance of each circuit to be adjusted to a specific value.

This oven has been used with satisfactory service on the X–15 aircraft and other experimental aircraft at the center. It has become so popular that it is used for virtually all thermocouple systems at the Flight Research Center.

POTENTIAL INDUSTRIAL APPLICATIONS

Thermocouple checking circuits and reference junctions have potential applications in nearly all large-scale thermocouple installations in industry. Often, thermocouples are individually checked on a regular schedule. Adoption of one of the circuits described in this chapter could represent a significant saving of time with a minimum of investment. In addition to the time saved by a central circuit check-out system over the individual inspection, the reliability of the temperature-measuring system could be increased by more frequent check-outs (with little additional cost).

Industrial instruments have built-in reference-junction compensation, but in unusual situations one of the three methods for reference junction compensation may be applicable to an industrial problem.

Abbreviations

Ag-0.37 Au/Con	Silver-0.37 atomic percent gold/constantan
Ag-0.37 Au/Au-2.1 Co	Silver-0.37 atomic percent gold/gold-2.1 atomic percent cobalt
Ag-0.37 Au/Au-0.03 Fe	Silver-0.37 atomic percent gold/gold-0.03 atomic percent iron
Al_2O_3	Aluminum oxide
BeO	Beryllium oxide
Ch/Al	Chromel/Alumel
Ch/Au-2.1 Co	Chromel/gold-2.1 atomic percent cobalt
Ch/Au-0.07 Fe	Chromel/gold-0.07 atomic percent iron
Ch/Con	Chromel/constantan
Cu/Ag-0.37 Au	Copper/silver-0.37 atomic percent
Cu/Au-2.1 Co	Copper/gold-2.1 atomic percent cobalt
Cu/Ni	Copper/nickel
Cu/347 SS	Copper/347 stainless steel
Fe/Con	Iron/constantan
Ir-40 Rh/Ir	Iridium-40 percent rhodium/iridium
LHe	Liquid helium
LH_2	Liquid hydrogen
LNG	Liquid natural gas
LN_2	Liquid nitrogen
LOX	Liquid oxygen
MgO	Magnesium oxide
Pt-30 Rh/Pt-6 Rh	Platinum-30 rhodium/platinum-6 rhodium
SiO	Silicon monoxide
ThO_2	Thorium oxide
W-5Re/W-26 Re	Tungsten-5 percent rhenium/tungsten-26 percent rhenium
ZrB_2	Zirconium diboride
ZrC	Zirconium carbide

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Subject Index

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